Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin

Nancy L. Shackell, Blair J.W. Greenan, Pierre Pepin, Denis Chabot and Anne Warburton (Editors)

Ocean and Ecosystem Sciences Division
Fisheries and Oceans Canada
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
Canada B2Y 4A2

2013

Canadian Manuscript Report of Fisheries and Aquatic Sciences 3012

Fisheries and Oceans Canada
Pêches et Océans Canada

Canada

Canadian Manuscript Report of Fisheries and Aquatic Sciences

Manuscript reports contain scientific and technical information that contributes to existing knowledge but which deals with national or regional problems. Distribution is restricted to institutions or individuals located in particular regions of Canada. However, no restriction is placed on subject matter, and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Manuscript reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts.*

Manuscript reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-900 in this series were issued as Manuscript Reports (Biological Series) of the Biological Board of Canada, and subsequent to 1937 when the name of the Board was changed by Act of Parliament, as Manuscript Reports (Biological Series) of the Fisheries Research Board of Canada. Numbers 1426 - 1550 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Manuscript Reports. The current series name was changed with report number 1551.

Rapport manuscrit canadien des sciences halieutiques et aquatiques

Les rapports manuscrits contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui traitent de problèmes nationaux ou régionaux. La distribution en est limitée aux organismes et aux personnes de régions particulières du Canada. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports manuscrits peuvent être cités comme des publications à part entière. Le titre exact figure audessus du résumé de chaque rapport. Les rapports manuscrits sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports manuscrits sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 900 de cette série ont été publiés à titre de Manuscrits (série biologique) de l'Office de biologie du Canada, et après le changement de la désignation de cet organisme par décret du Parlement, en 1937, ont été classés comme Manuscrits (série biologique) de l'Office des recherches sur les pêcheries du Canada. Les numéros 901 à 1425 ont été publiés à titre de Rapports manuscrits de l'Office des recherches sur les pêcheries du Canada. Les numéros 1426 à 1550 sont parus à titre de Rapports manuscrits du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 1551.

Canadian Manuscript Report
of Fisheries and Aquatic Sciences 3012

2013

Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin

by

Nancy L. Shackell[1], Blair J.W. Greenan[1], Pierre Pepin[2], Denis Chabot[3] and Anne Warburton[1]

Ecosystems and Oceans Science Sector
Fisheries and Oceans Canada

[1] Bedford Institute of Oceanography
P. O. Box 1006, Dartmouth, Nova Scotia B2Y 4A2
[2] Northwest Atlantic Fisheries Centre
P.O. Box 5667, St. John's, Newfoundland and Labrador A1C 5X1
[3] Institut Maurice-Lamontagne
850 route de la Mer, C.P. 1000, Mont-Joli, QC, G5H 3Z4

© Her Majesty the Queen in Right of Canada, 2013
PDF version: Cat. No. Fs97-4/3012E-PDF ISSN 1488-5387

Published by:
Fisheries and Oceans Canada
200 Kent Street
Ottawa, Ontario
K1A 0E6
Through the assistance and cooperation of the Council of Fisheries and Oceans Librarians (COFOL)

Correct citation for this publication:

Shackell, N.L., B.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Editors). 2013. Climate Change Impacts, Vulnerabilities and Opportunities (IVO) Analysis of the Marine Atlantic Basin. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

TABLE OF CONTENTS

LIST OF TABLES .... *x*

LIST OF FIGURES .... *xii*

ABSTRACT .... *xiii*

RÉSUMÉ .... *xiv*

PREFACE .... *xv*

Chapter 1 Description of the Atlantic Large Aquatic Basin as a habitat for marine fish and invertebrates (D. Chabot and D. Gilbert) *1*

1.1 INTRODUCTION 1
1.2 PRESENT CONDITIONS IN THE ATLANTIC LARGE AQUATIC BASIN 2
 1.2.1 Temperature 2
 1.2.2 Salinity 7
 1.2.3 Dissolved Oxygen 7
 1.2.4 pH 8
1.3 OCEANOGRAPHIC PROJECTIONS FOR THE ATLANTIC LARGE AQUATIC BASIN 9
 1.3.1 Temperature 9
 1.3.2 Salinity 10
 1.3.3 Dissolved Oxygen 10
 1.3.4 pH 12
1.4 ACKNOWLEDGMENTS 12
1.5 REFERENCES 12

Chapter 2 Physiology of water breathers: Effects of temperature, dissolved oxygen, salinity and pH (D. Chabot and S. Guénette) *16*

2.1 INTRODUCTION 16
2.2 TEMPERATURE 17
2.3 DISSOLVED OXYGEN 22
2.4 pH 28
2.5 SALINITY 32
2.6 CONCLUSION 34
2.7 ACKNOWLEDGEMENTS 35
2.8 REFERENCES 35

Chapter 3 Dynamics of lower trophic levels in the western North Atlantic: Past trends and anticipated changes under climate change (P. Pepin and R.E. Jamieson) *45*

3.1 INTRODUCTION 45
3.2 PHYTOPLANKTON 47
 3.2.1 Carbon Dioxide 49
 3.2.2 Temperature 52
 3.2.3 Phenology 59
 3.2.4 Harmful Algal Blooms 61
3.3 ZOOPLANKTON 63

3.3.1 Temperature Effects 63
3.3.2 Ecophysiology of Calanus and Likely Response to Climate Change 64
3.3.3 Phenology 65
3.3.4 Changes in Circulation and Influence on Community Structure 68
3.4. CONCLUSION: COMMUNITY STRUCTURE AND LINK TO THERMAL REGIME AND CONSEQUENCES FOR TRANSFER TO HIGHER TROPHIC LEVELS 70
3.5 REFERENCES 73

Chapter 4 A review of the physiological susceptibility of commercial species of fish and crustaceans of the northwest Atlantic to changes in water temperature, dissolved oxygen, pH and salinity (D. Chabot, S. Guénette and C. Stortini) 83
4.1 INTRODUCTION 83
4.2 DEMERSAL FISHES 84
4.2.1 American Plaice 84
4.2.2 Atlantic Cod 89
4.2.3 Atlantic Halibut 96
4.2.4 Greenland Halibut 99
4.2.5 Haddock 102
4.2.6 Redfish 105
4.3. Pelagic Fishes 109
4.3.1 Atlantic Herring 109
4.3.2 Atlantic Mackerel 113
4.3.3 Capelin 117
4.4. Crustaceans 121
4.4.1 Atlantic Lobster 121
4.4.2 Northern Shrimp 125
4.4.3. Snow Crab 130
4.5. DISCUSSION 135
4.5.1 Limitations of the Study 139
4.5.2 Perspectives 140
4.6 ACKNOWLEDGEMENTS 146
4.7 REFERENCES 146

Chapter 5 Life history, status and potential impacts of climate variability and change on Atlantic salmon with emphasis on eastern Canada (M.J. Robertson, J.B. Dempson, M.F. O'Connell and G. Chaput) 169
5.1 SUMMARY 169
5.2 INTRODUCTION 170
5.3 ATLANTIC SALMON LIFE HISTORY 171
5.3.1 Size and Growth in Freshwater 175
5.3.2 Size and growth at sea 177
5.4 TRENDS AND STATUS OF ATLANTIC SALMON 178
5.5 CLIMATE CHANGE IMPACTS TO ANADROMOUS ATLANTIC SALMON 180
5.5.1 Physiology 181
5.5.2 Species Distribution 182
5.5.3 Timing of Seasonal Events (Phenology) 182
5.5.4 Chemistry 183

5.6 CONCLUSION: ANTICIPATED CONSEQUENCES TO FISHERIES AND OCEANS CANADA (DFO) PROGRAMS FROM ATLANTIC SALMON AS A RESOURCE 183
5.7 REFERENCES 184

Chapter 6 Climate change and marine aquaculture in Atlantic Canada and Quebec (N. Feindel, L. Cooper, E. Trippel and T. Blair) 195
6.1 SUMMARY 195
6.2 INTRODUCTION 196
6.3 ECONOMIC VALUE AND PRODUCTION OF MARICULTURE IN ATLANTIC CANADA AND QUEBEC 197
6.4 PROFILES OF KEY CULTURED SPECIES IN ATLANTIC CANADA AND QUEBEC 198
6.4.1 Atlantic Salmon (*Salmo salar*) 198
6.4.2 Steelhead Trout (*Oncorhynchus mykiss*) 201
6.4.3 Arctic Charr (*Salvelinus alpinus*) 202
6.4.4 Atlantic Cod (*Gadus morhua*) 203
6.4.5 Blue Mussel (*Mytilus edulis*) 205
6.4.6 The American Oyster (*Crassostrea virginica*) 207
6.5 SUMMARY OF DIRECT AND INDIRECT EFFECTS OF CLIMATE CHANGE ON MARINE AQUACULTURE IN ATLANTIC CANADA AND QUEBEC 210
6.5.1 Direct Effects 210
6.5.2 Indirect Effects 211
6.6 KNOWLEDGE GAPS AND FUTURE RESEARCH CONSIDERATIONS 214
6.6.1 Salmonids 214
6.6.2 Shellfish 214
6.6.3 Modeling 214
6.7 GENERAL KNOWLEDGE GAPS 214
6.8 CONCLUSION 215
6.9 REFERENCES 216
Appendix 6.1: Maps of aquaculture sites in Atlantic Canada and Quebec 224
Appendix 6.2: Environmental thresholds for key cultured species in Atlantic Canada and Quebec 232

Chapter 7 Invasive species and climate change in Atlantic Canada (A. Locke) 241
7.1 SUMMARY 241
7.2 INTRODUCTION 242
7.3 PREDICTING THE EFFECTS OF CLIMATE CHANGE ON INVASIVE SPECIES IN ATLANTIC CANADA 243
7.4 TRANSPORT (SPECIES IN SOURCE REGION → ARRIVAL IN TARGET REGION 244
7.5 COLONIZATION (ARRIVAL IN TARGET REGION → SURVIVAL IN TARGET REGION) 246
7.6 REPRODUCTION (SURVIVAL IN TARGET REGION → ESTABLISHMENT IN TARGET REGION) 248
7.7 DISPERSAL (ESTABLISHMENT IN TARGET REGION → SPREAD TO NEW AREAS IN TARGET REGION) 249
7.8 DISCUSSION 250
7.9 REFERENCES 251

Chapter 8 Climate change impacts and vulnerability of marine species at risk in the Atlantic basin of Canada: A screening level analysis of climate change impacts and vulnerability (R. D. Walmsley) 256

8.1 Introduction and objectives 256
8.2 Background to this Assessment 258
  8.2.1 ACCASP Guidelines and Approach to the Atlantic Basin 258
  8.2.3 Impacts and Vulnerability Analysis 259
  8.2.4 Characteristics of the Atlantic Basin 261
  8.2.5 Climate Change Stressors and Impacts on the Aquatic Environment 262
  8.2.6 Changes in Climate Change Stressors over the Atlantic Basin Area 264
  8.2.7 Species at Risk 264
8.3 SPECIES AT RISK IN THE ATLANTIC BASIN 265
8.4 EXPOSURE ANALYSIS 270
  8.4.1 Fish 270
  8.4.2 Mammals 273
  8.4.3 Reptiles 274
  8.4.4 Molluscs 275
8.5 ANALYSIS OF SENSITIVITY 276
  8.5.1 Fish 277
  8.5.2 Cetaceans 280
  8.5.3 Pinnipeds 282
  8.5.4 Reptiles 283
  8.5.5 Molluscs 283
8.6 INTEGRATED IMPACTS AND VULNERABILITY ANALYSIS 283
8.7 Acknowledgements 287
8.8 REFERENCES 288

Chapter 9 Community and ecosystem-level effects of climate change in Canadian northwest Atlantic waters (H.P. Benoît and A.M. MacKinnon) 291
9.1 INTRODUCTION 291
9.2 SHIFTS IN GEOGRAPHIC DISTRIBUTION 292
  9.2.1 Observations—Macrofauna 292
  9.2.2 Observations—Plankton 293
  9.2.3 Prediction Under Climate Change 293
  9.2.4 Key Uncertainties 294
9.3. CHANGES IN THE SEASONAL TIMING OF RECURRING LIFE HISTORY EVENTS: PHENOLOGY 295
  9.3.1 Observations of Phenological Changes and Their Community-Level Implications 296
  9.3.2 Predictions Under Climate Change and Key Uncertainties 296
9.4 CHANGES TO FOOD WEBS AND THEIR CONSEQUENCES 297
  9.4.1 Mechanisms Underlying Possible Food Web Mediated Climate Change Effects 298
9.5 KEY ANTICIPATED CONSEQUENCES FOR DFO PROGRAMS 301
  9.5.1 Harvest Levels and the Application of the Precautionary Approach 301
  9.5.2 Keeping up With Changes in Stock Boundaries 302
  9.5.3 Increased Attention to the Need to Protect/Enhance Older and Larger Spawners in Exploited Living Resources 303
  9.5.4 Pressures Created by Changes in the Diversity, Intensity and Frequency of Agents that are Infectious to Fish 303
9.6 REFERENCES 303

Chapter 10 Analysis of DFO non-ecosystem services and operations in Atlantic Canada (B.J.W. Greenan and A. Warburton) 313

10.1 INTRODUCTION 313
10.2 Ranking the Uncertainty of Non-Ecosystem Impacts 315
10.3 Climate Drivers Affecting Non-Ecosystem Components of DFO Operations and Services 317
  10.3.1 Mean Sea Level Rise and Extreme Sea Levels 317
  10.3.2 Changes in Ocean Temperature and the Cryosphere 318
  10.3.3 Storms and Waves 319
  10.3.4 Air and Sea Surface Temperature Changes 320
  10.3.5 Ocean and Coastal Circulation Patterns 320
  10.3.6 Erosion 320
10.4 INCREASED DEMAND TO PROVIDE EMERGENCY RESPONSE SERVICES 321
  10.4.1 Emergency Response—increased Demand for Environmental Response 322
  10.4.2 Emergency Response Services—Increased Demand for Search and Rescue 324
  10.4.3 Emergency Response Services—Joint Rescue Coordination Centre 327
10.5. COASTAL AND MARINE INFRASTRUCTURE 329
  10.5.1 Comments on Coastal Exposure 330
  10.5.2 Coastal Infrastructure–Design Capacity and Structural Integrity Compromised 331
  10.5.3 Coastal Infrastructure—Need to Adapt Harbour Infrastructure 336
  10.5.4 Coastal Infrastructure—Increased Maintenance Due to Biological Activity 338
  10.5.5 Coastal Infrastructure—Structural Damage to Harbour Infrastructure 339
  10.5.6 Coastal infrastructure—Compromised by Rapid Coastal Erosion 341
  10.5.7 Coastal Infrastructure—Floating and Fixed Navigational Aids 342
  10.5.8 Coastal Infrastructure—Vessel Operational Requirements and Modifications 344
10.6. ACCESS AND NAVIGABILITY OF WATERWAYS 346
  10.6.1 Access and Navigability of Waterways—Ice Routing and Information Services 347
  10.6.2 Access and Navigability of Waterways—Ice Breaking Services 348
  10.6.3 Access and Navigability of Waterways—CHS Charts 350
  10.6.4 Access and Navigability of Waterways—CHS Charts and Chart Datum 351
  10.6.5 Access and Navigability of Waterways—Dredging 353
  10.6.6 Access and Navigability of Waterways—Floating and Fixed Aids 354
10.7 POTENTIAL OPPORTUNITIES PRESENTED BY CLIMATE CHANGE 355
10.8 GAPS 356
10.9 EXPERT OPINION 357
10.10 CONCLUSION 360
10.11 REFERENCES 361

APPENDIX: References produced by companion oceanographic trends and projections ACCASP team 364

LIST OF TABLES

Tables are numbered by chapter followed by order within chapter

Table 4–1 Qualitative summary of the expected impacts in 2060–2070 of climate warming on recruitment (R), distribution (D) and productivity (P) of some important commercial species of demersal and pelagic fishes and crustaceans in the three sub-basins of the Atlantic Large Aquatic Basin. 138
Table 6–1 Potential impacts of climate change on cultured marine species in the Atlantic basin 196
Table 6–2 Aquaculture, production (tonnes) and value (thousands of dollars), by Atlantic Provinces and Quebec—2010 197
Table 6–4 Atlantic Salmon (*Salmo salar*). 232
Table 6–5 Steelhead Trout (*Oncorhynchus mykiss*). 234
Table 6–6 Arctic Charr (*Salvelinus alpinus*). 234
Table 6–7 Atlantic cod (*Gadus morhua*). 235
Table 6–8 Blue Mussels (*Mytilus edulis*). 236
Table 6–9 American Oyster (*Crassostrea virginica*). 239
Table 8–1 Some climate-related threats and potential consequences to aquatic ecosystems based on spatial considerations 262
Table 8–2 List of species at risk for the Atlantic Basin—accessed from the Canadian Species at Risk Registry on 24th July 2012. 268
Table 8–3 Profile of climate change stressor exposure ratings for pelagic species in the Atlantic Basin. 271
Table 8–4 Profile of climate change stressor exposure ratings for demersal-benthic species in the Atlantic Basin. 271
Table 8–5 Profile of climate change stressor exposure ratings for diadramous species in the Atlantic Basin. 272
Table 8–6 Profile of climate change stressor exposure ratings exposure ratings for cetaceans in the Atlantic Basin. 273
Table 8–7 Profile of climate change stressor exposure ratings for pinniped species in the Atlantic Basin 274
Table 8–8 Profile of climate change stressor exposure ratings for reptiles in the Atlantic Basin. 275
Table 8–9 Profile of exposure ratings for mollusc species to climate change stressors in the Atlantic Basin. 275
Table 8–10 Temperature ranges for fish species at risk in the Atlantic Basin. 279
Table 8–11 Temperature ranges for cetacean species at risk in the Atlantic Basin. 281
Table 8–12 Ranking of sensitivity of seals to climate change stress factors 282
Table 8–13 Summary table listing vulnerability status of Atlantic Basin marine species at risk to climate change. 286
Table 10–1 IVO summary table uncertainty ranking 315
Table 10–2 Emergency response impacts listed in IVO summary table. 321
Table 10–3 Emergency response services—Increased demand for environmental response.... 322
Table 10–4 Emergency response services—Increased demand for search and rescue 324
Table 10–5 Emergency response services—Joint Rescue Coordination Centre 327

Table 10–6 Coastal infrastructure impacts listed in IVO summary table 329
Table 10–7 RPSS Inventory in Maritimes and Gulf 331
Table 10–8 Coastal infrastructure–design capacity and structural integrity compromised 331
Table 10–9 Coastal infrastructure—Need to be adapt harbour infrastructure 336
Table 10–10 Coastal infrastructure—Increased maintenance due to biological activity............ 338
Table 10–11 Coastal infrastructure—Structural damage to harbour infrastructure 339
Table 10–12 Coastal infrastructure—Compromised by rapid coastal erosion 341
Table 10–13 Coastal infrastructure—Floating and fixed navigational aids................................. 342
Table 10–14 Coastal infrastructure—Vessel operational requirements and modifications 344
Table 10–15 Impacts to access and navigability of waterways listed in IVO summary............... 346
Table 10–16 Access and navigability of waterways—Ice routing and information services....... 347
Table 10–17 Access and navigability of waterways—Ice breaking services................................ 348
Table 10–18 Access and navigability of waterways—CHS charts... 350
Table 10–19 Access and navigability of waterways—CHS charts and chart datum 351
Table 10–20 Access and navigability of waterways—Dredging 353
Table 10–21 Access and navigability of waterways—Floating and fixed aids............................. 354
Table 10–22 March 2012 DFO interviewees about climate change impacts to operations and services 358
Table 10–23 Technical experts specializing in DFO infrastructure 359

LIST OF FIGURES

Figures are numbered by chapter followed by order within chapter

Figure 1–1 Map of Atlantic Large Aquatic Basin as defined by the Aquatic Climate Change Adaptation Program (ACCASP). 2
Figure 1–2 Average sea surface temperature in winter (early March) for the Atlantic Large Aquatic Basin during 1999–2010. 4
Figure 1–3 Average sea surface temperature in spring (late May) for the Atlantic Large Aquatic Basin during 1999–2010. 5
Figure 1–4 Average sea surface temperature in summer (late August) for the Atlantic Large Aquatic Basin during 1999–2010. 6
Figure 1–5 Bottom levels of dissolved oxygen in the Estuary and Gulf of St. Lawrence in 2012. 8
Figure 2–1 Simplified model of aerobic scope as a function of temperature 19
Figure 2–2 Theoretical framework for the impact of hypoxia and acidification on the aerobic scope of marine fish and invertebrates 24
Figure 2–3 Conversion between concentration, saturation and pressure units used to measure dissolved oxygen. 25
Figure 5–1 Map showing the Salmon Fishing Areas (SFAs) of Newfoundland and Labrador, Nova Scotia, New Brunswick, and Prince Edward Island, and Management Zones (Qs) of Québec. 171
Figure 5–2 Generalized life cycle of the Atlantic Salmon. 173
Figure 5–3 Distribution of generalized groupings of stock types of self-sustaining populations of Atlantic Salmon in North America. 174
Figure 5–4 Distribution of generalized stock groupings by smolt (river) age of self-sustaining populations of Atlantic Salmon in North America. 177
Figure 5–5 Trends in abundance of small (< 63 cm, upper panel) and large (≥ 63 cm, lower panel) Atlantic Salmon for North America, 1969–2011. 179
Figure 6–1 Bay Management Areas, Salmon Aquaculture Sites and Other Species Sites in the Bay of Fundy. 224
Figure 6–2 Salmonid and Mussel Aquaculture Sites in Newfoundland and Labrador 2010. 225
Figure 6–3 Nova Scotia's Atlantic Salmon Aquaculture Areas. 226
Figure 6–4 Nova Scotia's Steelhead Trout Aquaculture Areas. 227
Figure 6–5 Mussel farms in PEI (Comeau et al. 2008). 227
Figure 6–6 Distribution of oyster sites in northern New Brunswick in 2005 228
Figure 6–7 Northern New Brunswick and PEI shellfish aquaculture sites. 229
Figure 6–8 Nova Scotia's Blue Mussel Aquaculture Areas. 230
Figure 6–9 Nova Scotia's American Oyster Aquaculture Areas. 231
Figure 7–1 Conceptual model illustrating the role of environmental filters at four steps of introduction of a species to a novel environment: (1) Transport, (2) Colonization, (3) Reproduction, (4) Dispersal. 243
Figure 8–1 Framework illustrating the elements of I&V analysis and how they are linked in risk analysis 260
Figure 8–2 Marine species at risk in the Atlantic Basin target area. 267

ABSTRACT

Shackell, N.L., B.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Editors). 2013. Climate Change Impacts, Vulnerabilities and Opportunities (IVO) Analysis of the Marine Atlantic Basin. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

In 2011, Fisheries and Oceans Canada (DFO) initiated the national Aquatic Climate Change Adaptation Services Program (ACCASP). The main objectives are to increase our understanding of the effects of climate change on aquatic systems, assess the risks to delivery of DFO's mandate, and develop climate change adaptation tools for DFO sectors. The first step was to assess the impact and probability of six previously identified climate change risks to the delivery of DFO's services to Canadians. This present report contains up-to-date information available on impacts of climate change on marine life, DFO infrastructure and on how DFO delivers emergency services in the Atlantic Basin. This report was dependent on, and is a companion to, numerous reports on the physical "Trends and Projections" of key oceanographic variables in the Atlantic Basin (listed in Appendix). The entire body of work (Trends and Projections analyses, Impacts, Vulnerabilities and Opportunities analyses) is a clear and strong demonstration of the importance of monitoring programs to our understanding, and to the delivery of DFO's mandate through evidence-based decision-making. The body of work formed the basis for a succinct CSAS Risk Assessment(http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2012/2012_044-eng.html) which was used to design research projects needed to fill gaps in our understanding, as well as to identify applied science-based tools to enable climate change adaptation.

RÉSUMÉ

Shackell, N.L., B.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Editors). 2013. Climate Change Impacts, Vulnerabilities and Opportunities (IVO) Analysis of the Marine Atlantic Basin. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

En 2011, Pêches et Océans Canada (MPO) a lancé le Programme des services d'adaptation aux changements climatiques en milieu aquatique (PSACCMA). Ses principaux objectifs sont d'augmenter notre compréhension des effets du changement climatique sur les systèmes aquatiques, des conséquences pour le mandat du MPO, et de développer des outils d'adaptation pour les différents secteurs du MPO. Six risques posés par le changement climatique ayant été identifiés au préalable, la première étape du programme était d'établir les impacts possibles de ces risques sur la capacité du MPO à réaliser son mandat auprès des canadiens et leur probabilité de se réaliser. Le présent rapport contient l'information la plus à jour sur les impacts possibles du changement climatique sur la vie aquatique, les infrastructures du MPO et sur la façon dont le MPO offre les services d'urgence dans le Bassin Atlantique. Ce rapport dépendait de nombreux rapports sur les tendances récentes et les projections des variables océanographiques clés dans le Bassin Atlantique, qui sont énumérés en annexe. Les travaux des deux groupes (les analyses sur les tendances et les projections et la présente revue des impacts, vulnérabilités et opportunités) démontre très clairement l'importance des programmes de monitorage pour notre compréhension des effets du changement climatique et pour la capacité du MPO à réaliser son mandat sur la base de faits établis. Le travail des deux groupes a constitué la base d'une évaluation de risques du Secrétariat canadien de consultation scientifique (SCCS) (http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2012/2012_044-fra.html). Cette évaluation a ensuite servi à concevoir des projets de recherche visant à combler des lacunes dans nos connaissances et à identifier des outils scientifiques qui aideront le MPO à s'adapter au changement climatique.

PREFACE

A goal of the Aquatic Climate Change Adaptation Services Program (ACCASP) is to assess the risk of climate change to the mandate of Fisheries and Oceans Canada (DFO). Based on that risk assessment, DFO will implement climate change adaptation strategies through increasing our scientific understanding and developing "tools" that will help managers make decisions. In previous reports (Interis 2005, 2012), six risks of climate change to DFO's mandate were identified:

Risk 1: Ecosystem and Fisheries Degradation and Damage;
Risk 2: Changes in Biological Resources;
Risk 3: Species Reorganization and Displacement;
Risk 4: Increased Demand to Provide Emergency Response;
Risk 5: Infrastructure Damage; and
Risk 6: Change in Access and Navigability of Waterways

This "Impacts Vulnerabilities and Opportunities" (IVO) report contains the updated, detailed information used for a formal "Large Aquatic Basin Risk Assessment" for the Atlantic Basin (http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2012/2012_044-eng.html). Four DFO Atlantic Regions (Gulf, Maritimes, Newfoundland and Labrador, Quebec) form the Atlantic Large Aquatic Basin. The DFO Atlantic Basin "Trends and Projections" team of physical oceanographers analysed global and local scale trends and projections in relevant ocean drivers (e.g., temperature, salinity, dissolved oxygen, pH, circulation). Authors of this IVO report were asked to assess climate change impacts within the context of what's expected for the Atlantic basin. The IVO report is a companion to a summary report on climate change Trends and Projections for the Atlantic Large Aquatic Basin (Loder et al. 2013) and is based on its many supporting reports and articles that are listed in the Appendix of this report. Please visit http://waves-vagues.dfo-mpo.gc.ca/waves-vagues/ to find trends and projection documents if URL addresses are not listed.

In this IVO report, Chapter 1 describes the Atlantic Basin, and reviews the geography and physical oceanography from an ecological perspective. Marine life's first response to environmental change is always physiological. Chapter 2 provides a primer on the mechanisms of physiological response to key oceanographic variables (temperature, dissolved oxygen, salinity and pH) and is recommended reading. Chapters 3-9 address Risks 1-3 as itemized above, and pertain to DFO sectors dealing with marine resources and ecosystems. While we were unable to comprehensively summarize all aspects of marine life (e.g., marine mammals and corals are notably missing), each chapter is a thorough review of its subject matter. Chapter 10 addresses Risks 4-6 as itemized above and pertain to the following DFO sectors: Canadian Coast Guard (CCG), Small Craft Harbours Directorate (SCH), Real Property Safety and Security (RPSS), and the Canadian Hydrographic Service (CHS). Chapter 10 details how projected changes in climate drivers will directly, or indirectly, impact DFO operations and services of non-ecosystem responsiblities.

The IVO team is indebted to the Trends and Projections team led by John Loder. We have made significant progress towards understanding potential climate change impacts in the Atlantic basin as a result. The following DFO staff are to be thanked for reviewing chapters on behalf of the IVO report authors: (arranged by Region) Gulf: Michel Biron, Mark Hanson, Wayne Fairchild; Quebec: Denis Gilbert, Martin Castonguay, Yvan Lambert; Maritimes: Andrea Carew, Andrew Cooper; Newfoundland and Labrador: Chuck Bourgeois, John Dower, Bob Gregory, Gary Maillet, Mike O'Connell. We also thank Gregor Reid of University of New Brunswick for his contribution.

A recommendation for the full citation of each chapter is provided on its first page.

Nancy L. Shackell, Blair J.W. Greenan, Pierre Pepin, Denis Chabot and Anne Warburton (Editors)

REFERENCES

Interis 2005. Climate Change Risk Assessment for Fisheries and Oceans Canada, Interis Consulting Inc. Ottawa. http://www.dfo-mpo.gc.ca/Science/oceanography-oceanographie/accasp/index-eng.html

Interis 2012. National Climate Change Risk Profile — 2012 Update. Interis Consulting Inc. Ottawa.http://www.dfo-mpo.gc.ca/Science/oceanography-oceanographie/accasp/index-eng.html

Loder, J.W., J. Chassé, P. Galbraith, G. Han, D. Lavoie and others. 2013. Summary of climate change trends and projections for the Atlantic Large Aquatic Basin off Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3051 (under revision)

Chapter 1 Description of the Atlantic Large Aquatic Basin as a habitat for marine fish and invertebrates

D. Chabot* and D. Gilbert

Institut Maurice-Lamontagne, Fisheries and Oceans Canada, P.O. Box 1000, Mont-Joli, QC, G5H 3Z4

*Correspondence: Denis.Chabot@dfo-mpo.gc.ca

Suggested Citation:

Chabot, D. and D. Gilbert. 2013. Description of the Atlantic Large Aquatic Basin as a habitat for marine fish and invertebrates. Ch. 1 (p. 1–15) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

1.1 INTRODUCTION

Based on physical properties, in particular bathymetry and temperature, three areas or sub-basins can be distinguished in the Atlantic Large Aquatic Basin (LAB): the Scotian Shelf/Slope and Gulf of Maine (SS-GM), the Gulf of St. Lawrence (GSL), including the Lower St. Lawrence Estuary (LSLE), the southern and northern GSL, and the Newfoundland and Labrador Shelf and Slope (NLSS) (Fig. 1–1). For a large-scale overview of the oceanographic setting of the LAB, see Loder et al. (1998) and, for a large-scale perspective on climate change in the NW Atlantic, see Annex 1 in Brock et al. (2012).

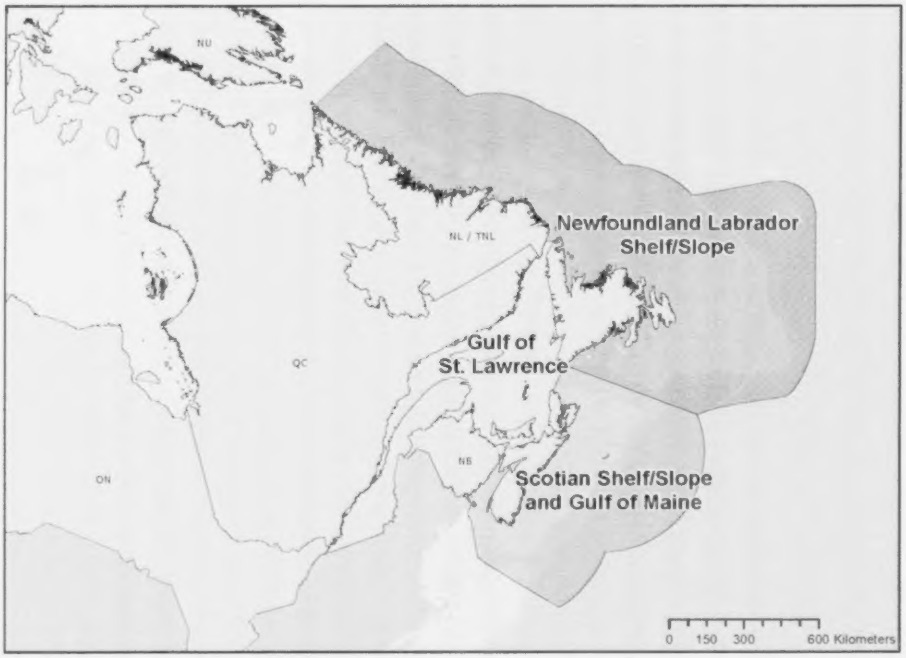
NU
NL / TNL
QC
ON
NB
Newfoundland Labrador Shelf/Slope
Gulf of St. Lawrence
Scotian Shelf/Slope and Gulf of Maine
0 150 300 600 Kilometers

Figure 1–1 Map of Atlantic Large Aquatic Basin as defined by the Aquatic Climate Change Adaptation Program (ACCASP).

The water properties most relevant for the physiology of marine fish and invertebrates are temperature (T), salinity (S), dissolved oxygen (DO) and pH. Other physical properties of the environment are no doubt important to marine species, such as substrate type, currents, turbidity (light transmission), ice cover, etc., but these four properties (T, S, DO, pH) are the most important for the physiology of water breathers (i.e., invertebrates and fish, excluding birds and marine mammals) and are the focus of this chapter.

First, the present conditions in the Atlantic LAB are summarized. Next, the changes that have been forecast by the Trends and Projections team for the four variables are summarized for two future periods, 2020–2030 and 2060–2070.

1.2 PRESENT CONDITIONS IN THE ATLANTIC LARGE AQUATIC BASIN

1.2.1 Temperature

Sea surface temperature (SST) is particularly important for the timing of planktonic blooms and larval development. As the larvae of most species of marine fish and invertebrates are pelagic and occupy the first few tens of meters of the water column, SST influences the availability of prey, in addition to larval physiology. In winter, SST is below 0 °C over most of the LAB (Fig. 1–2). Notable exceptions are a small polynya at the head of the Laurentian Channel, the south part of the NL Grand Bank, the south part of SS-GM, and the Slope waters to the south of the Grand Bank and Scotian Shelf.

Differences between summer and winter sea surface temperatures are typically around 15 °C (Ouellet et al., 2003). The maximum amplitude of the seasonal cycle of SST is found in the Northumberland Strait, where surface temperatures reach freezing point (about -1.5 °C) in the winter, and climb as high as 20 °C or higher in the summer. Areas with very strong tidal mixing, such as the mouth of the Bay of Fundy and the head of the Laurentian Channel, have the smallest seasonal cycle of SST. In those areas, SST differs by about 8 °C between summer and winter.

By late May, surface waters are still mostly below 0 °C off Labrador. Temperature increases on a northeast to southwest gradient, starting at 0–2 °C off Newfoundland and reaching ~10 °C in the southwest part of the SS-GM (Fig. 1–3). Most of the surface waters in the GSL are in the 4–6 °C range, with warmer water in coastal areas of the southern GSL.

In late summer, SSTs reach 2–8 °C off Labrador, 12–16 °C off the east coast of Newfoundland and the Grand Bank, most of the GSL, and parts of SS-GM (Fig. 1–4). The head of the Laurentian Channel is the coolest place in the GSL (~7–10 °C), whereas temperatures in the southern GSL, eastern Scotian Shelf (SS) and the GM reach 20 °C.

In summer, most of the Atlantic LAB is characterized by a warm surface layer, a cold intermediate layer and a deep layer. Conditions in the deep layer do not change much seasonally. Bottom temperatures and bottom salinities are intimately linked with bottom depth. Areas with bottom depth of 10m or less will have bottom temperatures that are relatively close to the surface temperatures. For bottom depths between about 40m and 100m, bottom temperatures will be typical of the CIL (between about -1 °C and 3 °C), and at greater bottom depths, the bottom temperatures are between about 3 °C and 10 °C (Colbourne et al., 2012; Galbraith et al., 2012; Hebert et al., 2012).

For recent information on past trends in upper-ocean temperature, see Galbraith and Larouche (2013), Galbraith et al. (2013), Han et al. (2013a,b), Hebert (2013a,b), and Loder et al. (2013a,b).

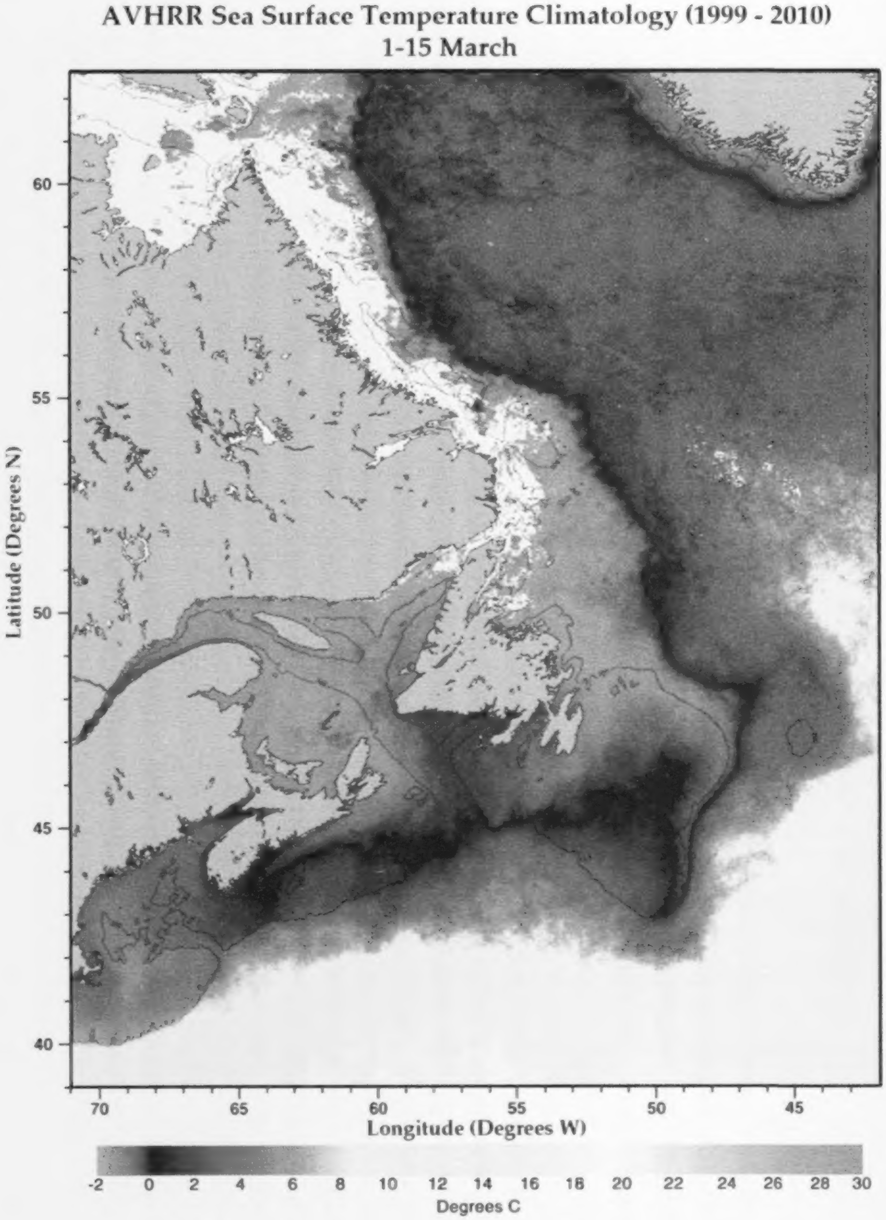
AVHRR Sea Surface Temperature Climatology (1999 - 2010)
1-15 March
Latitude (Degrees N)
60
55
50
45
40
70
65
60
55
50
45
Longitude (Degrees W)
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Degrees C

Figure 1–2 Average sea surface temperature in winter (early March) for the Atlantic Large Aquatic Basin during 1999–2010. http://www.bio.gc.ca/science/newtech-technouvelles/sensing-teledetection/composites-eng.php#images

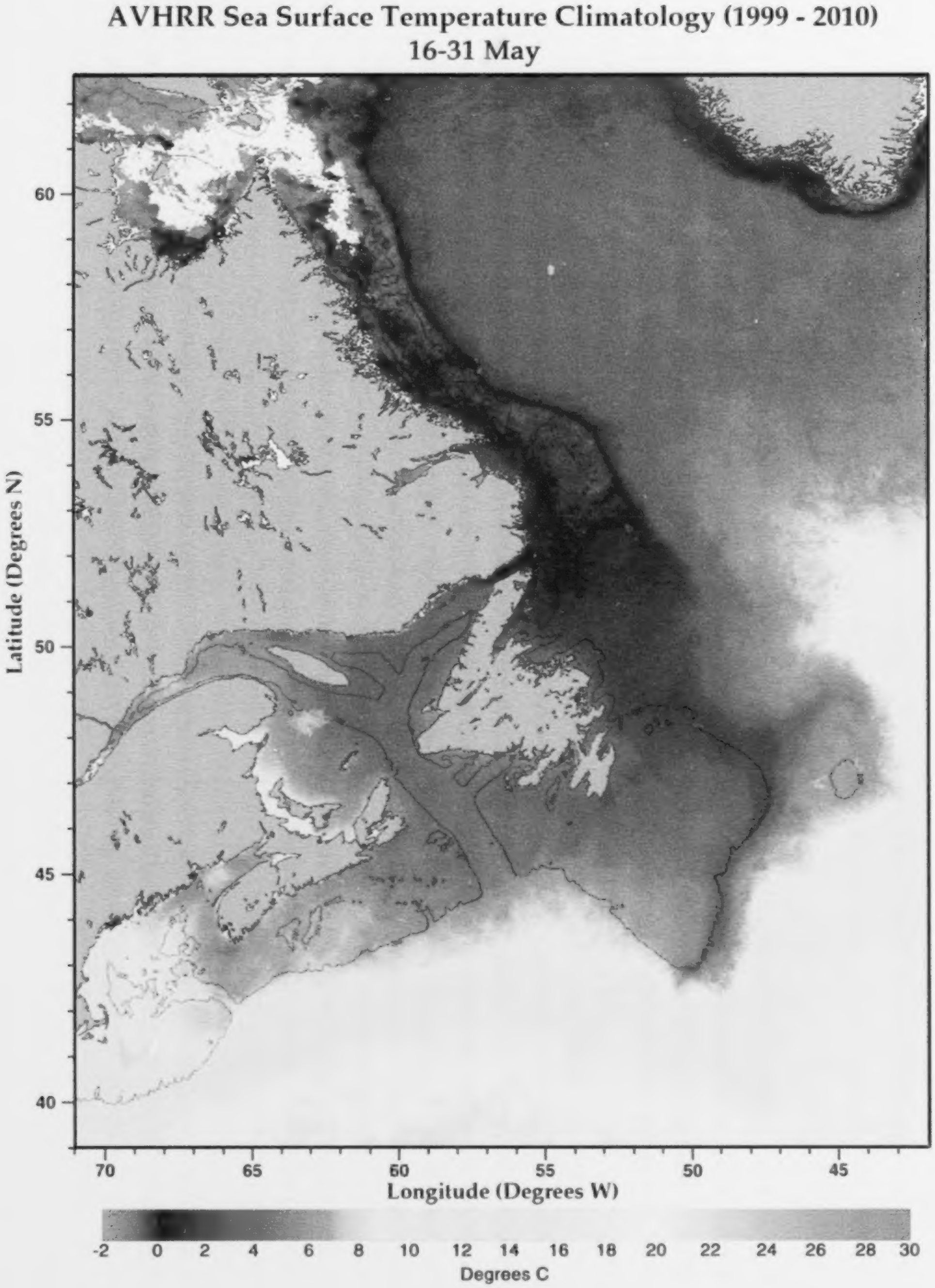
AVHRR Sea Surface Temperature Climatology (1999 - 2010)
16-31 May
Latitude (Degrees N)
60
55
50
45
40
70
65
60
55
50
45
Longitude (Degrees W)
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Degrees C

Figure 1–3 Average sea surface temperature in spring (late May) for the Atlantic Large Aquatic Basin during 1999–2010. http://www.bio.gc.ca/science/newtech-technouvelles/sensing-teledetection/composites-eng.php#images

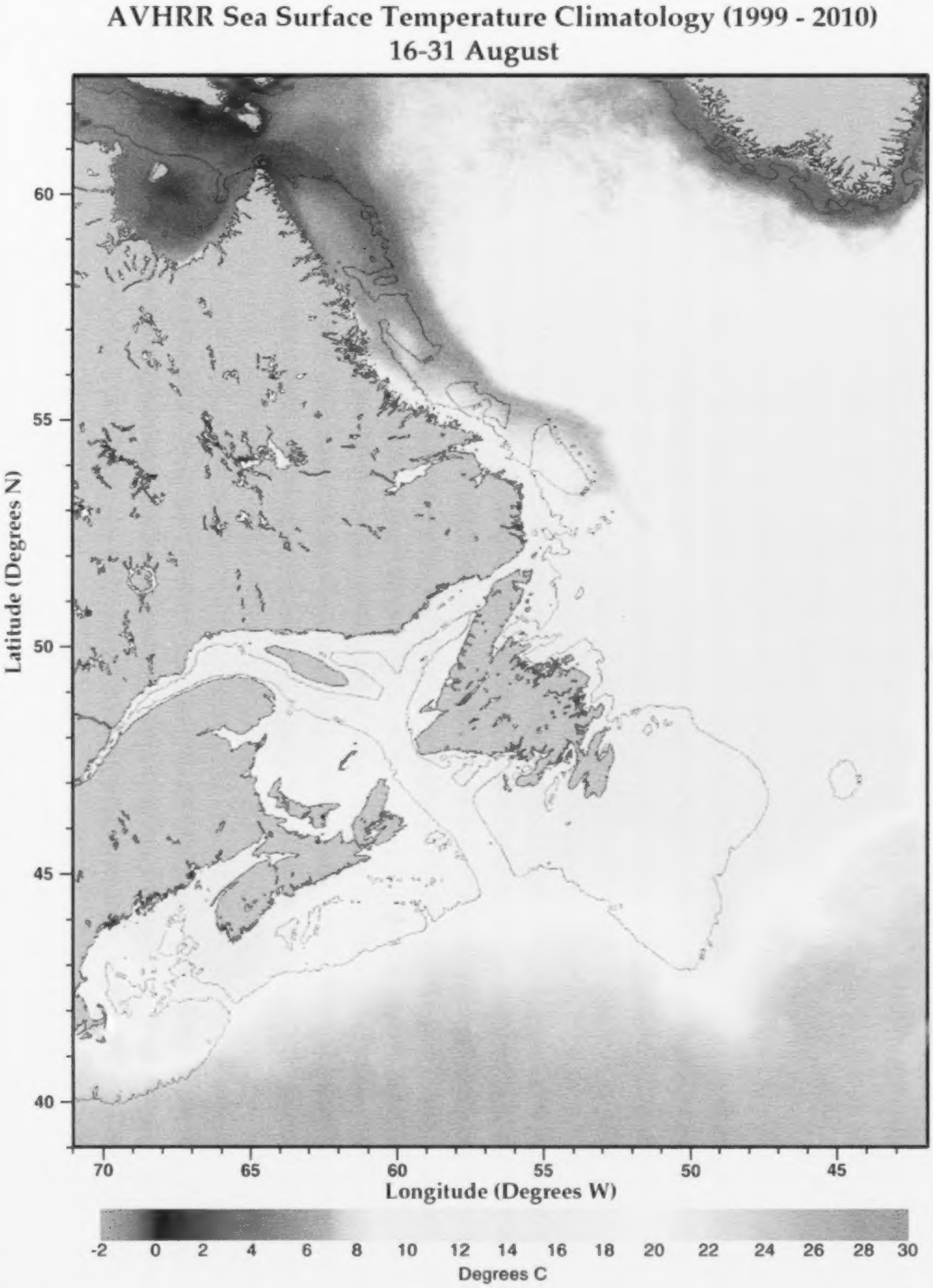
AVHRR Sea Surface Temperature Climatology (1999 - 2010)
16-31 August
60
55
50
45
40
Latitude (Degrees N)
70
65
60
55
50
45
Longitude (Degrees W)
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Degrees C

Figure 1–4 Average sea surface temperature in summer (late August) for the Atlantic Large Aquatic Basin during 1999–2010. http://www.bio.gc.ca/science/newtech-technouvelles/sensing-teledetection/composites-eng.php#images

1.2.2 Salinity

Throughout the Atlantic LAB, surface salinities are generally above 30, except in the LSLE and in the southern GSL where surface salinities between 25 and 30 are observed. Seasonal changes in surface salinity are generally small, with summer and winter surface salinities differing by 2 or less (Petrie et al., 1996a; Petrie et al., 1996b). Bottom salinities are between 29 and 36, and show seasonal variability in salinity less than 1 (Petrie et al., 1996a; Petrie et al., 1996b).

For recent information on past salinity trends in the Atlantic LAB, see Han et al. (2013a,b), Hebert (2013a,b), and Loder et al. (2013a).

1.2.3 Dissolved Oxygen

Hypoxia (low levels of dissolved oxygen, DO) is particularly severe in the GSL, including the lower estuary. The water in the deep channels of the GSL (Laurentian, Anticosti and Esquiman) and in the deep inner basins of the Scotian Shelf is of Atlantic origin. A mix of Labrador Current water (cold, rich in oxygen) and North Atlantic central water (warmer, poor in oxygen) enters into the GSL through the mouth of the Laurentian Channel, south of Newfoundland, and moves towards the head of the channels (Lauzier and Trites, 1958; Bugden, 1991; Gilbert et al., 2005). DO levels decrease progressively along the way because of respiration by fish and aquatic invertebrates, but mostly because of bacterial respiration (decomposition of organic matter which sinks to the bottom) (Coote and Yeats, 1979; Gilbert et al., 2005). In recent years, DO levels have been around 55–60% saturation (sat.) at Cabot Strait, but only 18–30% at the head of the channels (Gilbert et al., 2005; Galbraith et al., 2012) (Fig. 1–5).

Between the 1930s and the mid 1980s, DO levels decreased by half in the deep water of the St. Lawrence Estuary, primarily due to an increase in the proportion of North Atlantic Central Water (NACW) coming into the system. An increase in organic matter flow from the surface layer may also have played a secondary role, though this has not been quantified (Gilbert et al., 2005; Thibodeau et al., 2006; Gilbert et al., 2007). DO levels declined in the GSL as well (Genovesi et al., 2011). As the drop in DO between the 1930s and 1980s was accompanied by a warming of the water (~1.7 °C, Gilbert et al., 2005), respiration rates increased because chemical reactions in general, and metabolic rate in particular, tend to accelerate with temperature (Fry, 1971). Therefore, increased respiration contributed to the decrease in DO that took place during this period (Genovesi et al., 2011). Since the mid-1980s, DO levels in the deep channels of the GSL have been stable (Gilbert et al., 2007; Galbraith et al., 2012).

The southern Gulf of St. Lawrence is shallow and the bottom is in contact with the surface layer in coastal zones, and the Cold Intermediate Layer (CIL) elsewhere. Both the surface layer and the CIL are normoxic because of frequent mixing with the air and of photosynthetic oxygen production, although parts of the southern Gulf of St. Lawrence are in the 50–70% saturation range in September.

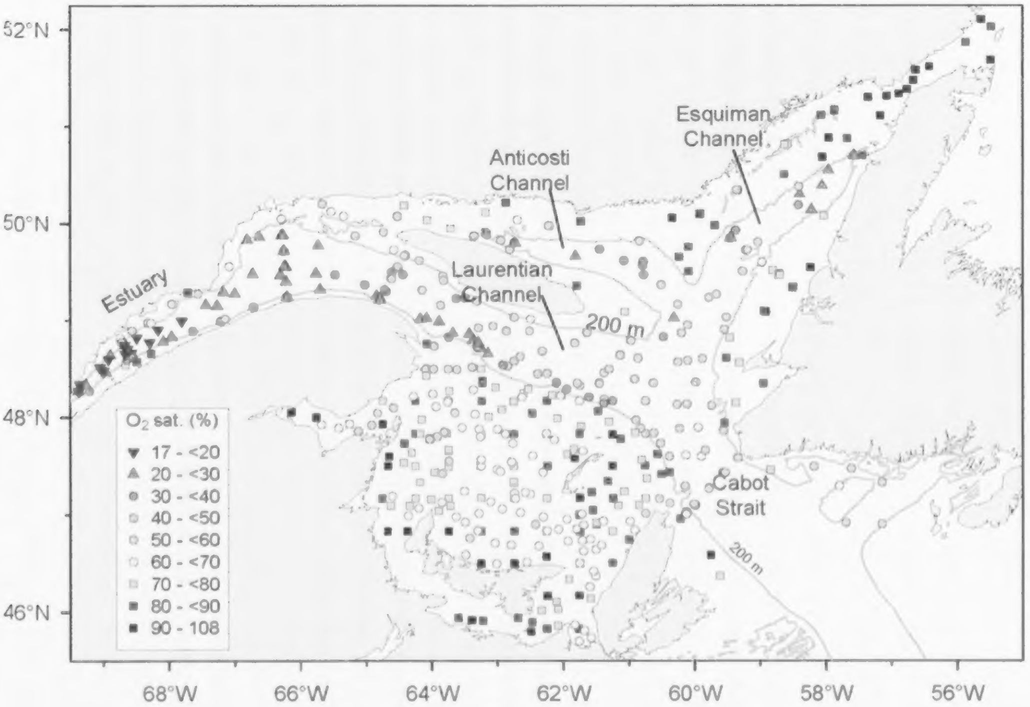
52°N
50°N
48°N
46°N
68°W
66°W
64°W
62°W
60°W
58°W
56°W
Esquiman Channel
Anticosti Channel
Laurentian Channel
Estuary
200 m
Cabot Strait
200 m
O_2 sat. (%)
▼ 17 - <20
▲ 20 - <30
● 30 - <40
○ 40 - <50
○ 50 - <60
○ 60 - <70
□ 70 - <80
■ 80 - <90
■ 90 - 108

Figure 1–5 Bottom levels of dissolved oxygen in the Estuary and Gulf of St. Lawrence in 2012. Oxygen data are from calibrated sensors deployed during several 2012 DFO surveys.

Dissolved oxygen is usually above 60% sat. on the SS, although the deep basins located in the central part of the SS have DO levels ranging between 40 and 60% sat. (Johnson et al., 2012). Deep waters in these basins are also very warm and are influenced by intrusions of Slope waters containing a large proportion of North Atlantic central water. Waters over the continental slope are also warm and hypoxic (Johnson et al., 2012, Fig. 1–5), with a subsurface oxygen minimum between 200 and 300 m depth (Gilbert, 2009).

The Labrador Shelf and Newfoundland Grand Bank are mostly influenced by the Labrador Current and bottom levels of DO are usually around 80% sat., with occasional values below 70% sat. (Kiceniuk and Colbourne, 1997).

Although hypoxia is mostly a deep-water problem in the Atlantic LAB, shallow waters that are subjected to large nutrient or organic inputs can also suffer from hypoxia, usually on a seasonal basis. Possible causes are the effluents of fish plants, aquaculture facilities, agriculture and municipal sewers. A few cases have been reported in the southern GSL (Scarratt et al., 2012).

1.2.4 pH

Surface pH in the GSL is ~8.07 (Mucci et al., 2011) and is similar elsewhere in the Atlantic LAB because the global value is ~8.1 (The Committee on the

Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, National Research Council of the National Academies, 2010). The deep channels in the EGSL are hypoxic (see above). As hypoxia's primary cause is extraction of oxygen by heterotrophs (respiration), a process that produces CO_2, hypoxic waters have a low pH (Burnett, 1997; Melzner et al., 2012). This is indeed the case in the EGSL with near-bottom values of pH starting at ~7.8 in Cabot Strait, and decreasing to 7.6–7.64 in the Estuary where hypoxia is most severe (Mucci et al., 2011). The pH in the deep layer of the Estuary is already lower than the pH predicted by many models for the surface water in 2100 (~7.75, Fabry et al., 2008; The Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, National Research Council of the National Academies, 2010). Low pH values are also expected on the slope of the SS-GM for the reasons given in the dissolved oxygen section.

1.3 OCEANOGRAPHIC PROJECTIONS FOR THE ATLANTIC LARGE AQUATIC BASIN

As part of the ACCASP initiative, time series of many environmental variables (air temperature, sea surface temperature, precipitation, ice coverage, salinity, water stratification, dissolved oxygen, pH) relevant to the study of climate change have been analyzed for trends. These trends, as well as output from global climate models and/or downscaled models, have been used to project the values of these parameters over 10–20 and 50–60 years. The main conclusions, as well as their uncertainty level, have been summarized in a high-level summary available in Loder et al. (2013a) and also in Appendix I of DFO (2013). Projected changes in sea surface temperature, water stratification, salinity, dissolved oxygen and pH are most relevant for the assessment of the impacts of climate change on marine exploited species and are summarized here from the high-level summary table and additional details provided in Loder et al. (2013a), unless otherwise noted.

Given the strong interannual variability caused by the North Atalntic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) cycles, the next 10–20 years are expected to be dominated by short-term environmental variability (Loder et al., 2013a). For instance the increase of temperature observed in the Bay of Fundy since 1960s is linked with to NAO activity. Long-term trends induced by global warming may not become apparent for 50 years, when climate change effects are expected to become more pronounced (Loder et al., 2013a).

1.3.1 Temperature

Over the last 30 years, ocean surface or near-surface temperature has warmed in all parts of the Atlantic LAB. Over the shorter horizon (10–20 y), annual means are likely to continue to increase in all three sub-basins, though there will likely be spatial differences in magnitude. In the southern part of the LAB (SS-GM), spring conditions should occur a bit earlier, and fall conditions later. There is a high level of confidence for these projections. These changes are very likely to become more pronounced in 50–60 years, particularly in the south. Seasonal means are likely to be 1–4 °C warmer in SS-GM and GSL, but likely only 0–2 °C warmer in NLSS. Confidence level is high, but only medium for NLSS. Spring conditions are likely to occur earlier, and fall conditions later, in all sub-basins.

Over the next 10–20 years, the cold intermediate layer (CIL) is moderately likely to become warmer (higher minimum temperature, lower area, thickness, volume), but the magnitude of these changes is uncertain. Natural variability is going to be very important. The same changes are considered likely over the longer term (50–60 years), but their magnitude is still considered uncertain. Less change is expected on ice-covered parts of the Labrador Shelf.

Below the CIL, temperature near the bottom increased in recent decades in SS-GM and GSL and further weak increases in temperature are moderately likely in these areas. Warming of bottom water is likely in most areas in 50–60 y. The magnitude of the change is not known, but will be less than for surface waters. A lag is expected between temperature changes taking place at the surface and those taking place in deep water.

For further information on projected upper-ocean temperature changes in the Atlantic LAB, see Chassé et al. (2013), Han et al. (2013a,b), Lavoie et al. (2013), and Loder and van der Baaren (2013).

1.3.2 Salinity

Within 10–20 years, surface salinity is moderately likely to decrease by a small amount (< 0.2) in all areas, more so at high latitude. It is very likely to decrease in all parts of the Atlantic LAB in 50–60 years. The magnitude should be 0.1–1, higher at high latitude. The projections are very similar for the salinity of bottom water, with natural variability dominating short-term changes. Over the long term, small decreases are likely in all seasons and all areas, except for the southern part of the LAB, where a small increase in salinity is moderately likely.

Within 10–20 years, near surface seasonal stratification is moderately likely to increase and to occur earlier, and the surfaced mixed-water depth is moderately likely to decrease, in all areas. Conversely, the end of stratification should occur later in fall. The same changes are very likely in 50–60 years.

For further information on projected upper-ocean salinity changes in the Atlantic LAB, see Chassé et al. (2013), Lavoie et al. (2013), and Loder and van der Baaren (2013).

1.3.3 Dissolved Oxygen

Dissolved oxygen (DO) will remain at saturation (100% sat.) in surface water because of diffusion from the atmosphere and oxygen production by phytoplankton. This is generally true for the surface and cold intermediate layers. In 10–20 years and even more so in 50–60 years, oxygen concentration will be reduced slightly in surface water, even though saturation level will remain 100%, because of the reduced solubility of oxygen when water temperature increases (García and Gordon, 1992). The solubility of oxygen in sea water (salinity = 32) is

11.1 mg l-1 at 2 °C, but only 7.8 mg l-1 at 18 °C, which is the temperature range corresponding to summer sea surface temperature over the Atlantic LAB at present. A warming of 2 °C would cause a drop in oxygen concentration of 0.5 mg l-1 in cold water (going from 2 to 4 °C) and 0.3 mg l-1 in warm water (going from 18 to 20 °C), even though water would remain at 100% sat.

Oxygen solubility also decreases with increasing salinity. Therefore the effect of warming would be compensated partially by a reduction of salinity in surface water: the solubility of 5 °C water is 10.4, 10.2 and 10.1 mg l-1 at salinities of 31, 33 and 35, respectively. Given the relatively small amplitude of the expected changes in salinity, their effects on oxygen solubility will be much less than those associated with expected changes in temperature.

Dissolved oxygen will be more problematic in deep water, because parts of the Atlantic LAB are already severely hypoxic, as explained earlier. Although present global climate models are too coarse for projections at the scale of the GSL with a numerical grid spacing larger than the width of the Laurentian Channel, DO levels in deep water are moderately likely to diminish over 10–20 years, and widespread reductions are very likely in 50–60 years.

Many factors are involved in the worsening of hypoxia in deep water. First, deep waters are moderately likely to warm slightly over 10–20 years, and likely to warm over 50–60 years (see above). This would cause a small reduction in oxygen concentration because of the reduced solubility of oxygen, as described previously for surface waters. Increased stratification, reduced depths of winter mixing (Loder, 2012) and reduced ventilation will also contribute to lower DO (both in saturation and concentration) because of the increased residence time of NACW in the main thermocline of the subtropical gyre due to a more northerly subduction (more time for respiration to remove oxygen), and more rapid respiration at warmer temperature. The deep (> 200 m) part of SS-GM will be more influenced by subtropical water (Loder, 2012), which is warm and poor in oxygen, and hence DO will be reduced. The deep water entering into the Laurentian Channel may contain a greater proportion of NACW than at present and be both warmer and more hypoxic. DO levels decrease as water moves toward the heads of the channels (Gilbert et al., 2005). It is impossible to predict the magnitude of the drop in DO in the deep channels of the GSL, but hypoxia is already severe (18–30% sat.) at the head of the Laurentian, Esquiman and Anticosti channels (Gilbert et al., 2005; Galbraith et al., 2012). Mucci et al. (2011) estimated that North Atlantic central water has last been exposed to the air about 12 years previously, by the time it reaches the mouth of the Laurentian Channel. They estimated that it takes another 4–6 years for this water to reach the St. Lawrence Estuary. Therefore, changes in temperature taking place at the surface would result in changes in DO content of the deep water in the Estuary approximately 16 years later, more if CC increases ventilation time, as suggested above.

Projected increases in SST will exacerbate shallow-water hypoxia in small bays and estuaries where it occurs, such as in the southern GSL, because of its effect on metabolic rate, including that of bacteria, and of the lower solubility of oxygen in warmer water.

For further information on projected DO changes in the Atlantic LAB, see Lavoie et al. (2013).

1.3.4 pH

In 10–20 years, a continuation of the recent trend of decreasing pH is likely. It should be in the order of 0.0–0.04 pH units in most areas, but more pronounced in the deep channels of the GSL, as worsening of hypoxia through respiration results in CO_2 production and lowering of pH. In the longer term (50–60 years), a widespread reduction in pH and shallowing of CaCO3 saturation depth is very likely. The decrease in pH should be > 0.1 in most areas and > 0.2 in the deep channels of the GSL. For comparison, global predictions are of a pH decrease in surface water of ~0.35 in 80 years (pH ~7.75 in 2100) and ~0.58 (pH ~7.58 in 2200) (The Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, National Research Council of the National Academies, 2010). As noted previously, pH is already 7.6–7.64 in the deep waters of the St. Lawrence Estuary. The predicted drop of > 0.2 units will bring pH down to ~7.4 in 2060–2070.

For further information on projected changes in pH in the Atlantic LAB, see Lavoie et al. (2013).

1.4 ACKNOWLEDGMENTS

We thank John Loder for his helpful comments and for pointing out which products from the Trends and Projections team contained the most up-to-date projections of temperature, salinity, dissolved oxygen and pH for tha Atlantic LAB.

1.5 REFERENCES

Brock, R. J., Kenchington, E. and Martinez-Arroto, A. (Editors). 2012. Scientific guidelines for designing resilient Marine Protected Area networks in a changing climate. Commission for Environmental Cooperation, Montréal, QC, Canada. 95 p. Available from http://www3.cec.org/islandora/en/item/10820-scientific-guidelines-designing-resilient-marine-protected-area-networks-in-changing-en.

Bugden, G.L. 1991. Changes in the temperature-salinity characteristics of the deeper waters of the Gulf of St. Lawrence over the past several decades. Can. Spec. Publ. Fish. Aquat. Sci., **113**: 139-147.

Burnett, L.E. 1997. The challenges of living in hypoxic and hypercapnic aquatic environments. Amer. Zool., **37**(6): 633-640.

Chassé, J., Perrie, W., Long, Z., Brickman, D., Guo, L. and Lambert, N. 2013. Regional atmosphere-ocean-ice climate downscaling results for the Gulf of St. Lawrence using the DFO Regional Climate Downscaling System. Can. Tech. Rep. Hydrogr. Ocean Sci. (under review).

Colbourne, E., Craig, J., Fitzpatrick, C., Senciall, D., Stead, P. and Bailey, W. 2012. An assessment of the physical oceanographic environment on the Newfoundland and Labrador Shelf during 2011. Can. Sc. Adv. Secr. Res. Doc. 2012/044: iv + 33 p. Available from http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2012/2012_044-eng.pdf

Coote, A.R. and Yeats, P.A. 1979. Distribution of nutrients in the Gulf of St. Lawrence. J. Fish. Res. Board Can., **36**: 122-131.

DFO 2013. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Atlantic Large Aquatic Basin. Can. Sci. Advis. Sec. Sci. Resp. 2012/044: 40 p. Available from http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2012/2012_044-eng.pdf

Fabry, V.J., Seibel, B.A., Feely, R.A. and Orr, J.C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES J. Mar. Sci., **65**(3): 414-432.

Fry, F.E.J. 1971. The effect of environmental factors on the physiology of fish *In* Fish physiology, vol. 6. *Edited by* W.S. Hoar and D.J. Randall. Academic Press, New York., pp. 1-98.

Galbraith, P.S. and Larouche, P. 2013. Trends and variability in eastern Canada sea-surface temperatures, pp. 1-18 *In* Aspects of climate change in the Northwest Atlantic off Canada. *Edited by* J.W. Loder, G. Han, P.S. Galbraith, J. Chassé, A. van der Baaren. Can. Techn. Rep. Fish. Aquat. Sci. 3045: x + 190 p. Available from http://www.dfo-mpo.gc.ca/Library/350208.pdf

Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Brickman, D., Pettigrew, B., Devine, L., Gosselin, A., Pettipas, R.G. and Lafleur, C. 2012. Physical oceanographic conditions in the Gulf of St. Lawrence in 2011. Can. Sc. Adv. Secr. Res. Doc. 2012/023: iii + 85 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_023-eng.pdf

Galbraith, P.S., Hebert, D., Colbourne, E. and Pettipas, R. 2013. Trends and variability in eastern Canada sub-surface ocean temperatures and implications for sea ice, pp. 57-72 *In* Aspects of climate change in the Northwest Atlantic off Canada. *Edited by* J.W. Loder, G. Han, P.S. Galbraith, J. Chassé, A. van der Baaren. Can. Techn. Rep. Fish. Aquat. Sci. 3045: x + 190 p. Available from http://www.dfo-mpo.gc.ca/Library/350208.pdf

Garcia, H.E. and Gordon, L.I. 1992. Oxygen solubility in seawater: better fitting equations. Limnol. Oceanogr., **37**(6): 1307-1312.

Genovesi, L., de Vernal, A., Thibodeau, B., Hillaire-Marcel, C., Mucci, A. and Gilbert, D. 2011. Recent changes in bottom water oxygenation and temperature in the Gulf of St. Lawrence: Micropaleontological and geochemical evidence. Limnol. Oceanogr., **56**(4): 1319-1329.

Gilbert, D. 2009. Argo float of the month - Crossing the Gulf Stream by a float with an oxygen sensor. Joint WMO IOC Technical Commission for Oceanography and Marine Meteorology. Available from http://w3.jcommops.org/FTPRoot/Argo/Doc/Floats/2009-05-Float.pdf

Gilbert, D., Sundby, B., Gobeil, C., Mucci, A. and Tremblay, G.- 2005. A seventy-two year record of diminishing deep-water oxygen in the St. Lawrence estuary: the northwest Atlantic connection. Limnol. Oceanogr., **50**(5): 1654-1666.

Gilbert, D., Chabot, D., Archambault, P., Rondeau, B. and Hébert, S. 2007. Appauvrissement en oxygène dans les eaux profondes du Saint-Laurent marin — Causes possibles et impacts écologiques. Nat. Can., **131**(1): 67-75.

Han, G., Colbourne, E., Pepin, P. and Tang, R. 2013a. Statistical projections of physical oceanographic variables over the Newfoundland and Labrador Shelf, pp. 73-84 *In* Aspects of climate change in the Northwest Atlantic off Canada. *Edited by* J.W. Loder, G. Han, P.S. Galbraith, J. Chassé, A. van der Baaren. Can. Techn. Rep. Fish. Aquat. Sci. 3045: x + 190 p. Available from http://www.dfo-mpo.gc.ca/Library/350208.pdf

Han, G., Ma, Z. and Bao, H. 2013b. Trends of temperature, salinity, stratification and mixed-layer depth in the Northwest Atlantic, pp. 19-32 *In* Aspects of climate change in the Northwest Atlantic off Canada. *Edited by* J.W. Loder, G. Han, P.S. Galbraith, J. Chassé, A. van der Baaren. Can. Techn. Rep. Fish. Aquat. Sci. 3045: x + 190 p. Available from http://www.dfo-mpo.gc.ca/Library/350208.pdf

Hebert, D. 2013a. Trends in temperature, salinity, density and stratification for different regions in the Atlantic Canadian shelf, pp. 33-42 *In* Aspects of climate change in the Northwest Atlantic off Canada. *Edited by* J.W. Loder, G. Han, P.S. Galbraith, J. Chassé, A. van der Baaren. Can. Techn. Rep. Fish. Aquat. Sci. 3045: x + 190 p. Available from http://www.dfo-mpo.gc.ca/Library/350208.pdf

Hebert, D. 2013b. Trends in temperature, salinity, density and stratification in the upper ocean for the Scotian Shelf, pp. 43-56 *In* Aspects of climate change in the Northwest Atlantic off Canada. *Edited by* J.W. Loder, G. Han, P.S. Galbraith, J. Chassé, A. van der Baaren. Can. Techn. Rep. Fish. Aquat. Sci. 3045: x + 190 p. Available from http://www.dfo-mpo.gc.ca/Library/350208.pdf

Hebert, D., Pettipas, R., Petrie, B. and Brickman, D. 2012. Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2011. Can. Sc. Adv. Secr. Res. Doc. 2012/055: iv + 42 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_055-eng.pdf

Johnson, C., Harrison, G., Head, E., Spry, J., Pauley, K., Maass, H., Kennedy, M., Porter, C., Yashayaeva, I. and Casault, B. 2012. Optical, chemical, and biological oceanographic conditions in the Maritimes Region in 2009 and 2010. Can. Sc. Adv. Secr. Res. Doc. 2012/012: iv + 64 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_012-eng.pdf

Kiceniuk, J.W. and Colbourne, E. 1997. Relating oxygen levels in the Newfoundland offshore waters to the physiology of Atlantic cod (*Gadus morhua*). Can. J. Fish. Aquat. Sc., **54**(S1): 81-87.

Lauzier, L.M. and Trites, R.W. 1958. The deep waters in the Laurentian Channel. J. Fish. Res. Board Can., **15**(6): 1247-1257.

Lavoie, D., Lambert, N., ben Mustapha, S. and van der Baaren, A. 2013. Projections of future physical and biogeochemical conditions in the Northwest Atlantic from CMIP5 Global Climate Models. Can. Techn. Rep. Fish. Aquat. Sci. 285: xiv + 156 p. Available from http://www.dfo-mpo.gc.ca/Library/349066.pdf

Loder, J. 2012. Climate change on the Scotian Shelf: Recent variability and a future outlook *In* Can. Sci. Advis. Sec. Sci. Resp.. *Edited by* R. Claytor and S. Leslie.., pp. 10-25. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_062-eng.pdf

Loder, J.W. and van der Baaren, A. 2013. Climate change projections for the Northwest Atlantic from six CMIP5 Earth System Models. Can. Tech. Rep. Hydrogr. Ocean Sci. 286: xiv + 112 p. Available from http://www.dfo-mpo.gc.ca/library/349550.pdf

Loder, J.W., Petrie, B. and Gawarkiewicz, G. 1998. The coastal ocean off northeastern North America: a large-scale view *In* The global coastal ocean: Regional studies and synthesis. *Edited by* A.R. Robinson and K.H. Brink. The Sea Vol. 11. John Wiley & Sons, Inc., pp. 105-133.

Loder, J.W., Chassé, J., Galbraith, P., Han, D., Lavoie, D., and others. 2013a. Summary of climate change trends and projections for the Atlantic Large Aquatic Basin off Canada. Can. Techn. Rep. Fish. Aquat. Sci. 3051 (under revision).

Loder, J.W., Wang, Z., van der Baaren, A. and Pettipas, R. 2013b. Trends and variability of sea surface temperature in the Northwest Atlantic from the HadISST1, ERSST, and COBE datasets. Can. Tech. Rep. Hydrogr. Ocean Sci. 292: viii + 36 p. Available from http://www.dfo-mpo.gc.ca/Library/350066.pdf

Melzner, F., Thomsen, J., Koeve, W., Oschlies, A., Gutowska, M.A., Bange, H.W., Hansen, H.P. and Körtzinger, A. 2012. Future ocean acidification will be amplified by hypoxia in coastal habitats. Mar. Biol., **160**: 1875-1888. doi:10.1007/s00227-012-1954-1.

Mucci, A., Starr, M., Gilbert, D. and Sundby, B. 2011. Acidification of Lower St. Lawrence Estuary Bottom Waters. Atmosphere-Ocean, **49**(3): 206-218. doi:10.1080/07055900.2011.599265.

Ouellet, M., Petrie, B., Chassé, J. 2003. Temporal and spatial scales of sea-surface temperature variability in Canadian Atlantic waters. Can. Tech. Rep. Hydrogr. Ocean Sci. 228: v + 30 p. Available from http://www.dfo-mpo.gc.ca/Library/270882.pdf

Petrie, B., Drinkwater, K., Gregory, D., Pettipas, R. and Sandström, A. 1996a. Temperature and salinity atlas for the Scotian Shelf and the Gulf of Maine. Can. Tech. Rep. Hydrogr. Ocean Sci. 171: v + 398 p. Available from http://www.dfo-mpo.gc.ca/Library/193505.pdf

Petrie, B., Drinkwater, K., Sandström, A., Pettipas, R., Gregory, D., Gilbert, D. and Sekhon, P. 1996b. Temperature, salinity and sigma-t atlas for the Gulf of St. Lawrence. Can. Tech. Rep. Hydrogr. Ocean Sci. 178: v + 256 p. Available from http://www.dfo-mpo.gc.ca/Library/198079.pdf

Scarratt, M., Chabot, D. and Gilbert, D. 2012. Hypoxia in the St. Lawrence Estuary and Gulf *In* Can. Manuscr. Rep. Fish. Aquat. Sci. 2986. *Edited by* H.P. Benoît, J.A. Gagné, C. Savenkoff, P. Ouellet and M.-N. Bourassa. 2986.., pp. 10-15. Available from http://www.dfo-mpo.gc.ca/Library/345310.pdf

The Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, National Research Council of the National Academies 2010. Ocean acidification. A national strategy to meet the challenges of a changing ocean. The National Academies Press. 175 p.

Thibodeau, B., de Vernal, A. and Mucci, A. 2006. Recent eutrophication and consequent hypoxia in the bottom waters of the Lower St. Lawrence Estuary: Micropaleontological and geochemical evidence. Mar. Geol., **231**(1): 37-50.

Chapter 2 Physiology of water breathers: Effects of temperature, dissolved oxygen, salinity and pH

D. Chabot*[1] and S. Guénette[2]

[1] Institut Maurice-Lamontagne, Fisheries and Oceans Canada, P.O. Box 1000, Mont-Joli, QC, G5H 3Z4

[2] Bedford Institute of Oceanography, Fisheries and Oceans Canada, P.O. Box 1006, Dartmouth, NS, B2Y 4A2

*Correspondence: Denis.Chabot@dfo-mpo.gc.ca

Suggested Citation:

Chabot, D. and S. Guénette. 2013. Physiology of water breathers: Effects of temperature, dissolved oxygen, salinity and pH. Ch. 2 (p. 16–44) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

2.1 INTRODUCTION

Water breathers (marine invertebrates and fish) are ectotherms and their body temperature is usually very close or identical to that of the water where they live. As chemical reactions are known to be temperature dependent, it is not surprising that the physiology of these animals is strongly influenced by temperature and that all animals have a range of temperatures that is compatible with their survival. Similarly, all but a few heterotrophic[1] organisms rely on oxygen to produce energy. With a few exceptions, heterotrophic organisms require a sufficient level of dissolved oxygen (DO) to survive. Although less obvious to non-physiologists, water salinity and pH also influence the physiology of marine invertebrates and fish.

The aim of this chapter is to review how these four important properties of water, temperature, DO, salinity and pH can influence the physiology, productivity and distribution of marine invertebrates and fish. All four properties are likely to be influenced by climate change in the Atlantic Large Aquatic Basin (LAB) (Chabot and Gilbert, 2013; Loder et al., 2013). Only water breathers are considered in this chapter, as marine mammals and birds are able to maintain their body temperature within a wide range of environmental temperatures. These organisms are also more isolated, physiologically, from the water medium and therefore are not influenced by changes in DO (they do not obtain their oxygen from the water), pH and salinity (their blood is not in contact with sea water).

---

[1] Organisms requiring complex organic substances for survival, essentially organisms unable to use photosynthesis

2.2 TEMPERATURE

In ectotherms, the rate of chemical processes is proportional to temperature within certain ranges. For this reason, temperature is described as a “controlling” factor for metabolic rate (Fry, 1971).

Temperature tolerance varies with species, population, latitudinal cline, and degree of seasonal variations (Pörtner and Farrell, 2008). It decreases with increasing level of organism complexity (Pörtner and Farrell, 2008). Within a species, tolerance is also linked to ontogenetic stages. The general pattern is that spawners, eggs and larvae, and large individuals are less tolerant to temperature increases than juveniles (Pörtner and Farrell, 2008; Pörtner and Peck, 2010). At one end of the spectrum, stenotherm[2] fish and invertebrates from polar waters, adapted to extreme and stable temperature conditions, do not have the capacity to sustain higher temperatures (Pörtner, 2001). In contrast, some intertidal invertebrates can sustain extreme temperatures by using metabolic depression, anaerobic energy production, and stress protection mechanisms (Pörtner and Farrell, 2008).

In most animals, energy requirements are met by aerobic respiration, that is, the degradation of substrates (proteins, lipids, carbohydrates) obtained in food by oxidative phosphorylation to produce ATP (Nelson and Chabot, 2011). The minimum level of energy expenditure to maintain homeostasis is called the standard metabolic rate (SMR). It covers things such as the cost of maintaining active potential in cell and mitochondrial membranes, some protein and RNA turnover, and the cost of blood circulation, respiration, hormone and enzyme synthesis (Frappell and Butler, 2004; Hulbert and Else, 2004). SMR does not allow for locomotion, digestion, reproduction or growth. Animals are able to use more energy so as to sustain such additional activities, but there are limits in their ability to extract oxygen from water, i.e., limits in the circulatory and ventilatory systems of the animals. The maximum rate of energy expenditure is called the maximum (or active) metabolic rate (MMR or AMR, the former will be used therein), and the difference between the MMR and SMR is called the aerobic scope (AS) (Fry, 1971). A large AS means that the animal has room to manoeuvre, in energetic terms: it can generate greater performance in locomotion and other energy demanding activities, such as digestion. AS therefore influences behaviour (prey acquisition, predator avoidance, intraspecific interactions including mating), survival, growth rate, reproductive output, etc.

---

[2] species capable of living only within a very narrow temperature range

The physiological mechanism proposed to explain temperature tolerance of ectotherms is the limitation of the capacity to deliver oxygen to tissues (Pörtner, 2001), also called oxygen- and capacity-limited thermal tolerance (OCLTT) (Clark et al., 2013). Generally speaking, the SMR of water-breathing animals increases exponentially with temperature. MMR, on the other hand, increases more rapidly with temperature at first, but reaches a maximum value and then either stabilizes or declines with further temperature increases. The difference between the two curves is the AS curve and it takes the shape of an inverted U: it is maximum at the optimal temperature (T_{opt}) for AS (Fig. 2–1). AS declines as temperature drops or increases from T_{opt} (Pörtner, 2001; Pörtner and Knust, 2007). Most animals cannot live for extended period when their AS is zero or worse, when they cannot even sustain SMR. The points on the AS–temperature curve where AS is nil are call lethal or critical temperatures (T_{cI} and T_{cII}, lower and upper critical temperatures). AS often remains very high at temperatures close to T_{opt}. The pejus (meaning "getting worse") temperatures (T_p) or thresholds (lower, T_{pI}, and upper, T_{pII}) are those where AS begins to decline more rapidly. Pejus thresholds are located well within critical temperatures, generally investigated for aquatic species (Pörtner, 2001; Pörtner, 2002). Different species and populations differ in their T_{opt}, T_{pI} and T_{pII}.

Ventilation and circulation responses constitute the first response of a fish or aquatic invertebrate at pejus temperatures. Temperatures beyond high and low T_p lead to reduced performance because tissue demands in oxygen exceed oxygen delivery. This is because of the slowing of circulation and ventilation in the cold, and their insufficient increase in the warm (Pörtner, 2001). When approaching T_c, the anaerobic metabolism is solicited. In most species, this cannot be sustained for long periods because of the accumulation of toxic metabolites such as lactate, and because it yields few ATP compared with aerobic metabolism, and therefore depletes energy reserves much faster. Pejus thresholds are understood as long-term limits for motor activity, growth and reproduction. Although these thresholds would be important for modelling for instance, they have only been defined for a few species. Most modelling studies use the observed temperature at which species are commonly found. This is an approximation of pejus thresholds, although it is possible that marginal habitats (in terms of temperature) represent conditions between T_p and T_c.

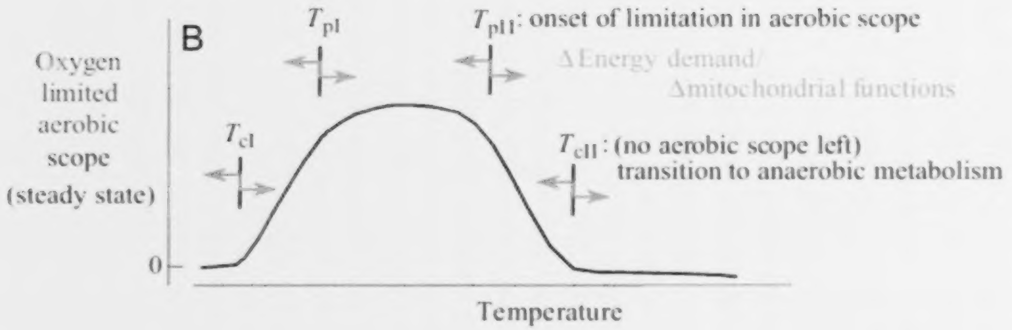

Figure 2–1 Simplified model of aerobic scope as a function of temperature (adapted from Pörtner, 2001 and Pörtner, 2002). Aerobic scope is at its maximum at the optimal temperature. It remains high within the lower and upper pejus temperature thresholds (T_{pI} and T_{pII}) which signal the onset of a rapid decrease in aerobic scope. Critical temperatures (T_{cI} and T_{cII}) signal the onset of anaerobic metabolism. The horizontal arrows signal the possible shift brought by seasonal adaptation.

Polar fish have specialized to optimise their AS in very cold water, but at the cost of being unable to adapt to warmer temperatures (Pörtner, 2001; Pörtner et al., 2008). They are stenothermic[3] and very vulnerable to climate warming. The high cost of adaptation to cold water and poor cold-water adaptability of eurytherms[4] explain the lower biodiversity in macrobenthic fauna at high latitudes.

Species that live in habitat where temperature is constantly warm, such as tropical species, also have a narrow thermal tolerance range compared with species from temperate climate, which are characterized by wider seasonal temperature swings (Stevens, 1989; Pörtner and Knust, 2007; Tewksbury et al., 2008). There are non-equatorial species that are adapted to warm habitats. Like tropical species, they have little capacity to adapt to yet warmer conditions (Stillman, 2003) and are therefore vulnerable to climate warming (Pörtner et al., 2008).

Eurythermic species, on the other hand, can adapt to seasonal variations or to extreme conditions relative to the general species thermal window. Seasonal acclimatization requires a limited shift or reshaping of the window of tolerance. Adaptation to cold temperatures is achieved by temporarily increasing mitochondrial density or mitochondrial aerobic capacity and other physiological adjustments (Pörtner and Knust, 2007). Cold-adapted eurythermic populations have a high SMR and if they are exposed to warmer waters, their SMR becomes too costly and requires a high feeding rate, possibly also reducing AS. Seasonal adaptation to warmer waters involves a decrease in baseline oxygen demand (Pörtner, 2001). In temperate zones, eurytherms can dynamically shift between summer and winter temperature regimes (Pörtner et al., 2001). These seasonal adaptations are less efficient (more costly) than the adaptation to permanent cold or warm water and are only maintained where water temperature fluctuates.

---

[3] very narrow thermal tolerance

[4] wide thermal tolerance

Thermal limitation in oxygen delivery is not the only mechanism by which temperature can influence the physiology of aquatic animals. For instance, inshore squids are recognised as ecological opportunists: their fast growth rate and short lifespan (rapid population turnover) enables them to adapt quickly to environmental changes (Pecl and Jackson, 2008). Yet, a rise in sea surface temperature (SST) would entail indirect negative effects for these squids. For instance, providing that food is not limiting and that temperature is within the thermal window (between T_{pI} and T_{pII}), warmer waters promote faster growth and shorter life spans in several species. On the other hand, warmer waters result in a faster incubation period and thus smaller size at hatching, which translates into smaller adult size and lower age and size at maturity. The potential increase in growth may be hindered by the additional requirement for food (and perhaps result in more cannibalism), and thus additional oxygen to process the food (Pecl and Jackson, 2008). Acidification would add another constraint and further limit growth (see below). A shorter life span has also several negative consequences on phenology and synchronicity of life-cycle events (spawning and migration onset) and may have considerable impacts on the species population dynamics (Pecl and Jackson, 2008).

Species with a wide latitudinal distribution may be eurythermic or they may have different populations, each one with a narrow thermal limit but adapted to local climate (Pörtner and Farrell, 2008). Within species, populations that occur at the warm end of the species' distribution are expected to be unable to adapt to anthropogenically induced warming of the water because they are likely already living at the upper end of temperature tolerance of the species (Pörtner et al., 2008). Similarly, populations living at the cold limit of the species' distribution are expected to be unable to adapt to further cooling. Because adaptation to cold makes local populations more stenothermic, they face declining AS in warmer water (Pörtner et al., 2008). However they may be able to adapt to slow warming.

Although the limitation in oxygen delivery to tissues hypothesis is appealing, temperature effects on ectotherms are complex. It is assumed that T_{opt} is the temperature at which the physiology of a species is optimized. Therefore, maximum growth rate and maximum feeding efficiency should be maximized at T_{opt} and remain very high between T_{pI} and T_{pII}. This is some support from this (e.g., T_{optG} (optimal temperature for growth) = T_{opt}, maximum growth at the temperature providing the greatest AS, Jobling, 1981), but some small differences have been documented in other species. For instance, the preferred temperature of ~1 kg Atlantic cod (*Gadus morhua*) has been established at 6.5 °C in the laboratory (Despatie et al., 2001), but T_{optG} for cod of this size is ~10 °C (Björnsson et al., 2007).

Some examples exist that do not comply with the limitation in oxygen delivery to tissues hypothesis: AS increases continuously with temperature, instead of peaking at T_{opt}, but collapses suddenly just before T_{cII} (Clark et al., 2013). Empirical evidence is required for a larger number of species to see if such examples are rare and the general principal of the thermal limitation in oxygen delivery to tissues hypothesis is a valid principle, or if this hypothesis requires modifications or even replacement, as suggested by Clark et al. (2013). For now, it can be concluded that the two pejus temperatures represent the range of temperatures at which a species can comfortably reside, although other factors, such as prey availability and quality are also involved in determining growth rate and T_{optG} in the field is not necessarily T_{opt} obtained in the laboratory by measuring AS.

Fish and crustaceans do have some control on their temperature. Firstly, mobile animals can avoid unfavourable temperatures and seek more favourable ones. This is often tested in the laboratory: fish that are allowed to chose their temperature when placed into a tank with a temperature gradient are expected to select the same temperature, regardless of their acclimation temperature. Less mobile species may not be able to do so directly, but wide dispersal of at least one life stage, usually the eggs and larvae, accompanied by differential survival of the other phases, will also result in such species changing their distribution with changing climate.

Food supply is another important criteria affecting the distribution of animals. Some authors have tried to tease out how food supply, which is density dependent, and temperature, which is not, interact when animals decide where to settle or live, and thus in defining species distributions. One first possibility is that only food supply matters, and fish select their habitat based on optimal foraging theory. Another is that temperature matters most, and that fish or other aquatic animals will select their habitat based on the scope for growth (essentially, the AS described above). A third possibility exists, where animals select the temperature which maximises growth while taking into account the food supply. Thus when food is not limited, fish select the temperature that maximizes AS, but as population density increases (or possibly also when competition with other species increases), food becomes limiting. The energy gain is maximized by selecting colder water, which reduces the metabolic rate required for maintenance (Fry, 1971), thus leaving more energy available for growth (Brett and Groves, 1979; Crowder and Magnuson, 1983). This hypothesis has been called the behavioural energetics hypothesis (Crowder and Magnuson, 1983; Wildhaber and Crowder, 1990) or alternatively, the growth rate potential model (Tyler and Brandt, 2001). This hypothesis is appealing on a bioenergetics point of view and indeed many species do use colder water when their abundance increases, including Atlantic cod and American plaice (*Hippoglossoides platessoides*) in the Gulf of St. Lawrence (Swain and Kramer, 1995; Swain and Morin, 1996; Swain, 1997; Swain and Morgan, 2001). Laboratory experiments confirmed that cod and plaice select colder temperatures when fed low rations, compared with fish fed ad libitum, a decrease of 2.5 °C for cod (Despatie et al., 2001) and 0.6 °C for plaice (Morgan, 1993).

But some predictions of the behavioural energetics hypothesis are not well supported by the data. The main cause of variations in food supply is population density. Whereas three Newfoundland American plaice populations did select warmer temperatures after a major decline in population size, as predicted by the behavioural energetics hypothesis, the southern GSL population did not (Swain and Morgan, 2001). For most fish species that do select colder temperatures when facing a limited food supply, the temperature decrease should be even greater to truly maximize energy gains (Mac, 1985; Wildhaber and Crowder, 1990). Recent studies concluded that fish do not use growth potential (i.e., energy available for growth, obtained by integrating temperature and food supply) in selecting habitat (Wildhaber and Crowder, 1990; Tyler and Brandt, 2001; Wildhaber and Lamberson, 2004). Instead, temperature is more important than food in habitat selection by fish (Wildhaber and Crowder, 1990; Wildhaber and Lamberson, 2004). The results of Wildhaber (2001) led him to suggest a new hypothesis that better agrees with the data observed in his and many other experiments on fish: at their thermal preferendum, fish would select habitat based on food availability and quality. But the value of similar food patches would be lowered ("discounted") at other temperatures, the amount of discounting being proportional to the deviation from the preferred temperature (Wildhaber, 2001; Wildhaber and Lamberson, 2004). This hypothesis works well in explaining the choice of food patches at different temperatures, but it is not entirely satisfactory to explain why fish held in a gradient tank at a low ration do not remain at their preferred temperature, but instead select a colder temperature, in partial support of the behavioural energetics hypothesis. Much progress has been accomplished in the 1990s and 2000s to understand how food and temperature interact in habitat selection by fish, but some details are yet to be resolved. Further, in a field situation, other factors influence habitat choice, such as predation risk (e.g., Kristiansen, 2001) and sediment type (particularly for flatfishes). Because of these conflicting priorities, fish need not be expected to select the temperature that is predicted from models where only some of the many factors influencing choice in the field are considered.

At a large geographic scale, current fish distributions are the expression of their thermal tolerances (Pörtner and Farrell, 2008). The geographical limits are defined by occasional thermal extremes or shock occurring in winter in the northern part of the distribution, and in the summer in the southern part of the distribution (Pörtner and Peck, 2010). As water temperature increases, fish are expected to move their center of distribution to continue living within their preferred temperature range. In the northern part of their distribution, the growth and fecundity of aquatic breathers are expected to increase as a consequence of changes in energy budgets (Pörtner, 2001). While thermal tolerance broadly defines what can be considered available habitat, tolerance to other factors (DO, salinity, pH) can further decrease habitat availability. Finally, biotic factors (prey availability, predator abundance) will also influence fish distribution.

2.3 DISSOLVED OXYGEN

As stated above, most aquatic ectotherms require oxygen for survival, and their productivity, linked to their AS, is based on the ability of their circulatory and ventilatory systems to deliver oxygen to tissues. As a result, reductions in DO have the potential to reduce AS and the energy budget of aquatic breathers. For this reason, Fry (1947; 1971) has called DO a limiting factor for metabolic rate. At a given temperature, it lowers MMR, and therefore AS as well. Over a range of temperatures, low DO values also restrict the pejus and critical temperature ranges (Fig. 2–2) (Pörtner and Farrell, 2008). Decreasing values of DO are of a particular concern when accompanied by an increase in temperature, as is expected with climate change (Chabot and Gilbert, 2013; Loder et al., 2013), because ectothermic organisms have an increased metabolic rate in warmer water, and thus require more oxygen (Fry, 1971). Further, warm water contains less oxygen (lower oxygen solubility) even when the water is in equilibrium with air (García and Gordon, 1992).

Oxygen diffuses from the air into water until its partial pressure (or tension) is the same in both media (100% saturation, or approximately 21.3 kPa, or ~21% of 1 atmosphere, equivalent to the proportion of oxygen in air). This defines normoxia. Concentration units such as mg, ml or µmol l^{-1} (µM) are often used to measure DO (1 ml = 1.43 mg = 44.66 µmol) (Fig. 2–3). However, concentrations units require that temperature and salinity be reported as well. Further, it is the difference between the partial pressure of oxygen (PO_2) in water and in the blood that facilitates the diffusion of oxygen into the blood (respiration) (Davis, 1975; Hofmann et al., 2011), making this unit (or the % sat.) preferable when discussing the biological impacts of dissolved oxygen.

The photic zone tends to be normoxic or even slightly hyperoxic because the proximity with air allows the diffusion of oxygen into water and because oxygen is produced by phytoplankton in daytime. Dissolved oxygen is reduced where oxygen is removed through respiratory or chemical processes faster than it is replenished from the atmosphere or by photosynthesis (Rabalais, 2009; Scarratt et al., 2012). Stratification of the water column makes diffusion of oxygen from surface water to deep water difficult, which favours the development of oxygen deprived water down the water column. Eutrophication can also lead to hypoxia: the increased primary production resulting from increased nutrients availability results in increased detritus deposition. This in turn increases bacterial oxygen consumption in the water column and near the bottom (Diaz and Rosenberg, 1995; Cloern, 2001; Gray et al., 2002; Rabalais, 2009; Breitburg et al., 2009; Kemp et al., 2009; Rabalais et al., 2010; Zhang et al., 2010a). Sometimes, hypoxic water, such as water from permanent ocean oxygen minimum zones, is advected onto coastal shelves, and can cause rapid drops in DO (Hofmann et al., 2011).

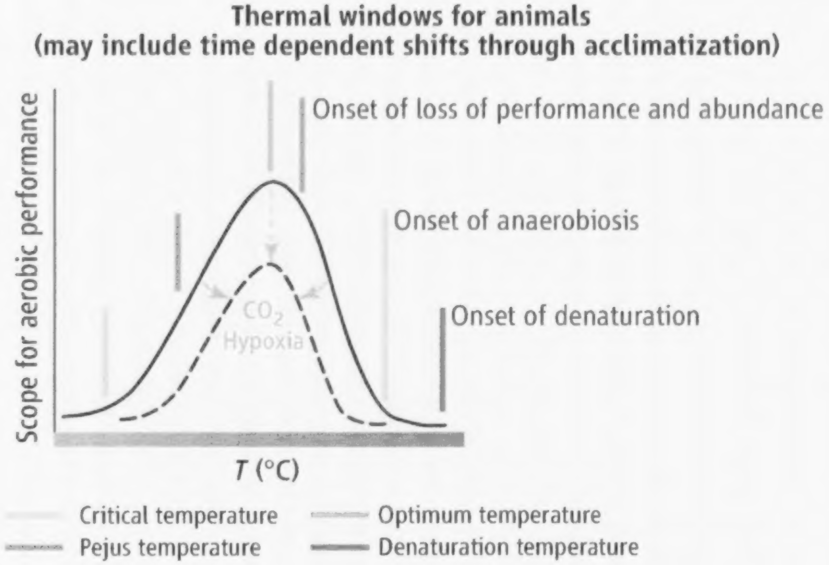
Thermal windows for animals
(may include time dependent shifts through acclimatization)
Scope for aerobic performance
Onset of loss of performance and abundance
Onset of anaerobiosis
Onset of denaturation
CO_2
Hypoxia
T (°C)
Critical temperature
Optimum temperature
Pejus temperature
Denaturation temperature

Figure 2–2 Theoretical framework for the impact of hypoxia and acidification on the aerobic scope of marine fish and invertebrates (from Pörtner and Farrell, 2008).

The increasing number of watersheds that are nutrient-enriched due to human activity has fuelled a rapid increase in the number of hypoxic and anoxic zones around the world, especially in estuaries and on inner continental shelves (Pihl, 1994; Diaz and Rosenberg, 1995; Diaz, 2001; Diaz and Rosenberg, 2008; Rabalais et al., 2010). Global warming could worsen this situation:

- Increasing water temperature reduces oxygen solubility.
- Aquatic breathers, including bacteria, have a faster metabolic rate in warmer water.
- The human population continues to increase and be concentrated along shorelines.
- Detritus will decompose faster, using more oxygen.

Further, climate change is likely to modify oceanic circulation patterns and slow down ocean ventilation, two processes that can potentially worsen present hypoxic conditions in the Atlantic LAB and enhance the conditions that cause hypoxia in the southern part of the Atlantic LAB and the Gulf of St. Lawrence (conditions described in Gilbert et al., 2005).

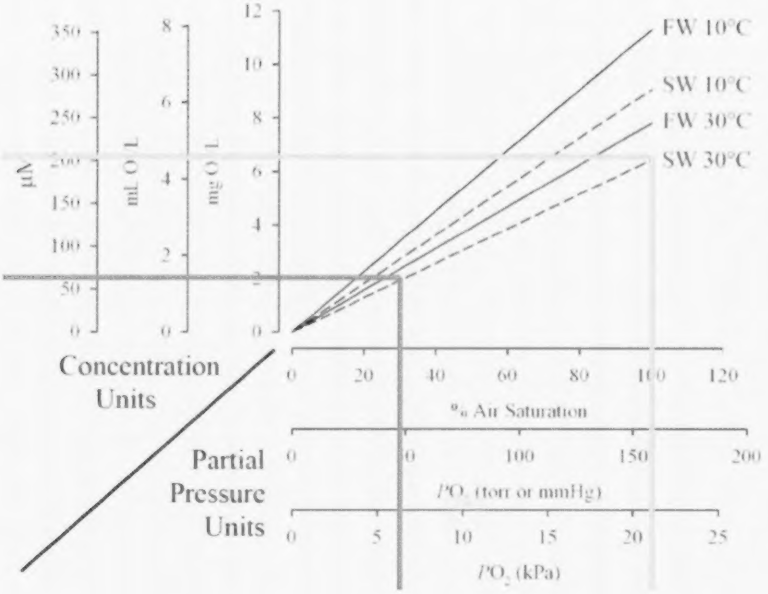

Figure 2–3 Conversion between concentration, saturation and pressure units used to measure dissolved oxygen. Concentration units are salinity and temperature dependent, i.e., 2 mg l^{-1} corresponds to a greater oxygen pressure in warm than in cold water. Conversely, oxygen is more soluble in cold and fresh water than in warm salty water. The green line corresponds to normoxia. The red line is the Scientific Committee for Oceanic Research (SCOR) Working Group 128 hypoxic threshold. For both lines, the position of the vertical component is unaffected by salinity and temperature, whereas the position of the horizontal component depends on temperature and salinity. In this example, the conditions in the Gulf of Mexico are used. From Rabalais et al. (2010).

Severe hypoxia can result in emigration of mobile species, mass mortality of fishes and invertebrates, changes in species dominance, trophic links and ecosystem structure, loss of biodiversity and of total biomass (Dyer et al., 1983; Tyson and Pearson, 1991; Uzars, 1994; Rabalais et al., 2002; Lim et al., 2006; Montagna and Ritter, 2006; Pollock et al., 2007; Rabalais et al., 2010). These large-scale consequences represent the sum of the effects on individual species, which differ in their tolerance to low DO levels (e.g., Davis, 1975; Vaquer-Sunyer and Duarte, 2008; Ekau et al., 2010; Haselmair et al., 2010).

Studies that aim to quantify the extent of hypoxia (surface area, volume) in an ecosystem often require a definition of a hypoxia threshold. Different values have been used, reflecting mostly the varying stamina of the taxa under investigation. Commonly used thresholds are < 1 ml l^{-1} (Rosenberg et al., 1991), 2 ml l^{-1} (Rosenberg, 1980; Diaz and Rosenberg, 1995; Diaz and Rosenberg, 2008; Levin et al., 2009), and 2 mg l^{-1} (Diaz, 2001; Rabalais et al., 2002; Rabalais et al., 2009). As stated previously, concentrations units are tied to the temperature and salinity where authors worked. Thus, 2 mg l^{-1} in the Gulf of Mexico is 30% sat. (assuming 25 °C, S = 35, Rabalais et al., 2002), whereas the same 2 mg l^{-1} is more severe hypoxia (20%) in the deep channels of the Gulf of St. Lawrence (assuming 5 °C and S = 33.5, Galbraith et al., 2012).

Expressing the threshold in saturation units is more useful, making it independent of local conditions. The Scientific Committee for Oceanic Research (SCOR) Working Group 128 agreed to consider a general value for hypoxia of 30% sat. (Rabalais et al., 2010). In the deep waters of the Gulf of St. Lawrence, this corresponds to 3 mg l^{-1}, 2.1 ml l^{-1} or 94 µM. The St. Lawrence estuary, the western part of the Gulf of St. Lawrence, and the head of the Anticosti and Esquiman Channels in the northeastern Gulf of St. Lawrence are hypoxic using this definition, and have been hypoxic since the middle of the 1980s (Gilbert et al., 2005; Gilbert et al., 2007; Chabot and Gilbert, 2013).

The use of a threshold underestimates the true impact of hypoxia for many species that suffer sublethal (or even lethal) effects above the chosen threshold (Vaquer-Sunyer and Duarte, 2008). Hypoxia imposes a continuum of effects on an ecosystem, with decreasing DO levels affecting an increasingly large number of taxa and causing increasingly severe effects on these taxa (e.g., Tyson and Pearson, 1991; Gray et al., 2002). In many studies, especially those dealing with single species, hypoxia is used to describe all DO levels where the species of interest begins to be negatively impacted by DO, with effects proportional to the severity of hypoxia (e.g., Claireaux et al., 1995; Plante et al., 1998; Chabot and Dutil, 1999; Pollock et al., 2007; Breitburg et al., 2009; Dupont-Prinet et al., 2013). This is the approach taken by Chabot et al. (2013).

The first response to hypoxia is often behavioural. Mobile organisms can avoid or move out of hypoxic areas (Tyson and Pearson, 1991; Burnett, 1997; Chabot and Claireaux, 2008). Aquatic breathers have oxygen sensors and they can detect oxygen gradients (Whitmore et al., 1960; Das and Stickle, 1994; Claireaux et al., 1995; Schurmann et al., 1998; Wannamaker and Rice, 2000). But hypoxia avoidance requires that alternative habitats are available and that an oxygen gradient exists between the organism's position and the alternative habitat (this may not be the case when hypoxic water suddenly invades a large zone). There are many examples of hypoxia avoidance, both in the laboratory (Whitmore et al., 1960; Das and Stickle, 1994; Claireaux et al., 1995; Schurmann et al., 1998; Wannamaker and Rice, 2000) and in the field (Kolar and Rahel, 1993; Burnett, 1997; Childress and Seibel, 1998; Bell and Eggleston, 2005). Hypoxia avoidance, even when it is possible, is not without cost. It can result in the use of suboptimal habitats in terms of temperature or salinity, or force aquatic breathers to live at higher density, causing food depletion, or a greater predation risk (Kramer, 1987; Kolar and Rahel, 1993; Eby and Crowder, 2002; Bell and Eggleston, 2005; Eby et al., 2005). Depending on a species' tolerance to hypoxia and the severity of hypoxia, it may be preferable to remain in hypoxic water than to move elsewhere. Other behaviours exist to avoid or alleviate hypoxia, such as air breathing or using water close to the air-water interface (Kramer, 1987), but these are not relevant in the context of the Atlantic LAB, where hypoxia is almost exclusively a deep water issue (Scarratt et al., 2012).

Organisms may remain in hypoxic water, either because they are sessile, sedentary, or because there is no better-oxygenated habitat within reach, or because these habitats are suboptimal and less attractive than the hypoxic habitat. Water breathers facing a decrease in DO can attempt to maintain oxygen delivery by increasing gill ventilation and perfusion, or by increasing blood oxygen carrying capacity (for reviews, see Perry and McDonald, 1993; Wu, 2002).

If the tissue oxygen supply cannot be maintained, the AS of the animal is reduced and DO becomes a limiting factor (sensu Fry, 1971). The extent of AS loss is proportional to the severity of hypoxia (Claireaux and Lagardère, 1999; Claireaux et al., 2000; Lefrançois and Claireaux, 2003; Chabot and Claireaux, 2008). A first consequence of a reduced AS is performance loss, such as a reduction in the maximum sustainable swimming speed (e.g., Dutil et al., 2007). But aquatic breathers do not use their full AS very often and a small reduction is probably not too costly.

More severe hypoxia (the meaning of this depends on each species' tolerance to hypoxia) reduces AS to a degree which requires aquatic breathers to reduce costly activities such as normal daily locomotion (Schurmann and Steffensen, 1994; Eriksson and Baden, 1997; Herbert and Steffensen, 2005), digestion (Jordan and Steffensen, 2007; Zhang et al., 2010b; Christen, 2012) and food consumption (Petersen and Pihl, 1995; Chabot and Dutil, 1999; Thetmeyer et al., 1999; Buentello et al., 2000; Bell et al., 2003). The usual consequence of these cost-cutting measures is a reduction in growth rate (Bejda et al., 1992; Petersen and Pihl, 1995; Secor and Gunderson, 1998; Chabot and Dutil, 1999; Thetmeyer et al., 1999; Wang et al., 2009; Sun et al., 2012).

Other possible consequences of a reduced AS are impaired reproductive success (Wu et al., 2003; Marcus et al., 2004; Thomas et al., 2006; Shang et al., 2006; Landry et al., 2007) and a reduced hatching success for eggs (Diez and Davenport, 1990; Mejri et al., 2012). Further, a lower aerobic capacity (including lower capacity to repay oxygen debt), coupled with reduced maximal swimming speed, can result in a lower capacity to catch prey and a higher vulnerability to predation or fishing gear (Chabot and Dutil, 1999; Chabot and Claireaux, 2008; Ekau et al., 2010).

In many species, lower activity and growth rates begin to appear in moderate hypoxia (< ~60–70% sat.) (Chabot and Dutil, 1999, Atlantic cod *Gadus morhua*; Foss et al., 2002, spotted wolffish *Anarhichas minor*; Wei et al., 2009, Chinese shrimp *Fenneropenaeus chinensis*), but in more tolerant species, normal growth rates can be maintained until DO levels approach the lethal level (McNatt and Rice, 2004, menhaden *Brevoortia tyrannus* and spot *Leiostomus xanthurus*; Dupont-Prinet et al., 2013, Greenland halibut, *Reinhardtius hippoglossoides*).

The critical oxygen level ($O2_{crit}$, P_{crit}, level of no excess activity), a common measure of hypoxia tolerance, is reached when DO is so low that AS becomes nil (Fry and Hart, 1948; Fry, 1971; Burnett, 1997; Schurmann and Steffensen, 1997). At this and lower DO levels, most water breathers must increase their use of anaerobic pathways of ATP production. In addition to much lower ATP yields, these pathways have toxic by-products like lactate, and only short-term survival is possible (Burnett, 1997; Wu, 2002; Bickler and Buck, 2007; Seibel, 2011). Very hypoxia-tolerant species have a low O_{2crit}, and further, they can survive long periods at DO levels lower than O_{2crit}. This is achieved by a combination of three responses: metabolic suppression to a level below SMR, usually by down-regulating protein synthesis and ion pumping, tolerance to metabolic by-products such as protons and lactate, and avoidance of or protection against cellular injury following reoxygenation (for a review, see Bickler and Buck, 2007).

Tolerance to a low concentration of oxygen varies among taxonomic groups, species and stages. Among marine water breathers, hypoxia tolerance is generally least for fishes and crustaceans, and greater in echinoderms, cnidarians and annelids, whereas it is highest in molluscs, but there is a high degree of variability within taxonomic group (Gray et al., 2002; Purcell et al., 2007; Vaquer-Sunyer and Duarte, 2008; Ekau et al., 2010). Diaz and Rosenberg (1995) also found polychaetes to be generally hypoxia-tolerant. In the Estuary and Gulf of St. Lawrence, Bourque (2009) found that some small polychaetes from the families Spionidae, Oweniidae, and Ampharetidae were more abundant in the Estuary (the most severely hypoxic stations), whereas polychaetes of the family Maldanidae were absent there but were well represented at better oxygenated stations.

Little is known of the relative hypoxia tolerance of planktonic species in the Atlantic LAB. Hypoxia is only a concern for species living in deep, hypoxic water. Copepods do spend the winter in deep water, but as hypoxia-tolerant cysts. Otherwise, copepods are usually found in normoxic water in the Estuary and Gulf of St. Lawrence (Plourde et al., 2002; Descroix et al., 2005). Many gelatinous zooplanktons have low oxygen consumption rates and many species are hypoxia-tolerant (Purcell et al., 2007).

There are some instances of seasonal shallow-water hypoxia in the southern Gulf of St. Lawrence (Scarratt et al., 2012). Few of the coastal species found in the Atlantic LAB have been studied, but some species are known to be hypoxia tolerant, such as the blue mussel, *Mytilus edulis*, and the softshell clam, *Mya arenaria* (Hoos, 1973), while others have an intermediate tolerance to hypoxia, except for their larval stages, which are more sensitive, such as the American lobster, *Homarus americanus*, rock crab, *Cancer irroratus*, and the sand shrimp *Crangon septemspinosa* (Miller et al., 2002; Vaquer-Sunyer and Duarte, 2008).

2.4 PH

Increased CO_2 concentration and partial pressure in the atmosphere result in greater diffusion of CO_2 into seawater. Although some of this CO_2 remains as a dissolved gas, most reacts with H_2O to form carbonic acid, H_2CO_3. This quickly forms a bicarbonate ion, HCO_3^- and a free H^+, which lowers pH. Another reaction can take place, carbonate (CO_3^{2-}) can combine with H^+ to form HCO_3^-. The net effect of the dissolution of CO_2 in seawater is to increase the concentrations of H^+, H_2CO_3 and HCO_3^- and decrease that of CO_3^{2-} (Raven et al., 2005). The lowering of pH (increased H^+ concentration) is the reason increased CO_2 diffusion into seawater is called acidification. The main problems with acidification are the lower availability of carbonate ions (higher solubility of carbonate), extra-cellular acid-base regulation, oxygen carrying capacity of the blood, and narrowing of the thermal window. These are explained next.

Many marine organisms, including coccolithophores, foraminifera, corals, coralline algae echinoderms, molluscs and crustaceans, build tests, shells and carapaces by combining carbonate and calcium ions to form calcium carbonate, $CaCO_3$. The lower concentration of CO_3^{2-} that accompanies acidification makes it more difficult, and more energetically costly, to built exoskelettons. Most calcifying organisms studied so far show a decrease in calcification or shell mass in response to elevated CO_2 and reduced pH, although for some of these organisms it took pH levels much lower than those predicted for 2100 (The Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, National Research Council of the National Academies, 2010). For instance, mussels (*Mytilus galloprovincialis*) subjected to long-term low pH (7.3, lower than predicted for 2100, pH = 7.75) show lower metabolic, growth and calcification rates (Michaelidis et al., 2005).

Another problem for calcifying organisms is that low pH water becomes "corrosive" for shells, increasing the cost of maintenance (for a review, see Kroeker et al., 2010). The intertidal snail, *Nucella lamellose*, appears able to maintain the rate of shell deposition at pH of 7.8 (~predicted level in year 2100) and 7.54 (~predicted level in year 2200), but the shell mass gain was less than in the control group, the loss being attributed to shell dissolution under low pH conditions (Nienhuis et al., 2010). In addition to shell dissolution because of the high solubility of carbonate ions at low pH, some invertebrates dissolve their shell to produce calcium and carbonate ions in an attempt at regulating their extracellular pH. *Mytilus galloprovincialis* is one example (Michaelidis et al., 2005).

Some exoskeletons are less susceptible to dissolution/erosion: crustacean carapaces contain chitin, which may act as a biological barrier against erosion (Ries et al., 2009; Kroeker et al., 2010). The carbonate-containing matrix of some molluscs is also less soluble than pure $CaCO_3$ (Melzner et al., 2012). Calcifying invertebrates can compensate for the greater solubility of the carbonate ion by increasing calcification rate (Kroeker et al., 2010), but doing so increases their energy demand, which is likely to interfere with growth rate (lower AS because of increased SMR).

Examples abound of molluscs being negatively impacted by ocean acidification. In their review, Kroeker et al. (2010) concluded that possible outcomes of ocean acidification are lower growth rates, reduced reproductive output and decreased survival. In their meta-analysis, decreased survival and calcification were the most pronounced effects. Because species-specific life history characteristics and protection mechanisms result in wide variations in response within taxonomic groups (e.g., Ries et al., 2009), the meta-analysis could not detect significant effects by taxonomic groups for several indicators. However, it showed positive effects of acidification for fish and crustaceans, the organisms that are covered in this chapter on marine fisheries, but without investigating the mechanisms involved.

Most heterotrophic organisms excrete CO_2, produced as a by-product of respiration, using a concentration gradient from high internal to low external dissolved CO_2. If external dissolved CO_2 rises, higher internal CO_2 concentration is necessary to maintain this gradient, potentially affecting acid-base balance in the organism (Burnett, 1997; The Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, National Research Council of the National Academies, 2010; Melzner et al., 2012). Heavily calcified organisms such as echinoderms, bryozoans, cnidarians and molluscs generally have a low capacity to regulate extra-cellular pH, which fluctuates passively depending on water physicochemistry (Pörtner, 2008). In some echinoderms and molluscs, acid-base regulation can involve using the exoskeleton to produce calcium ions (shell dissolution) (Burnett, 1997; Seibel and Walsh, 2003). Bivalves are considered not to alter their extracellular pH (Melzner et al., 2012). Crustaceans and fish, the focus of this study, compensate for this acidosis with more active, but energetically more costly, mechanisms involving ion pumping (Burnett, 1997; Seibel and Walsh, 2003; Melzner et al., 2009; Melzner et al., 2012). There is a correlation between buffering capacity and metabolic rate in marine animals (Seibel and Walsh, 2003).

The oxygen-carrying capacity of fish haemoglobin and crustacean haemocyanin is influenced by plasma pH, but more precisely by the pH found within red blood cells. This is called the Bohr effect (Schmidt-Nielsen, 1990; Brauner and Randall, 1998). Differences in oxygen pressure (PO_2) insure that haemoglobin picks up oxygen in the gills by diffusion (greater PO_2 in water than haemoglobin) and releases oxygen to the tissues (greater PO_2 in haemoglobin than tissues). This is enhanced by the Bohr effect, whereby pH is lowered in the gills, where CO_2 is excreted. This increases the oxygen-affinity of the transport pigment (haemoglobin in fish). On the contrary, pH is lowered in tissues, where CO_2 is produced, this time reducing the oxygen affinity of the pigment, facilitating the release of oxygen to the tissues (Brauner and Randall, 1998; Seibel and Walsh, 2003; Fabry et al., 2008). An increase in water or plasma CO_2 in the gills could therefore interfere with oxygen binding in the gills (Seibel and Walsh, 2003). This could be even worse in teleost fish, where the Root effect (lowering the blood's carrying capacity of O_2) has been demonstrated. Fish usually have several isoforms of haemoglobins and some of them have a lowered affinity with oxygen when pH is low. This permits massive unloading of oxygen. The Root effect normally permits the release of oxygen in the swim bladder or in the retina of the fish (Schmidt-Nielsen, 1990; Pelster and Randall, 1998) by regulating red blood cell pH to low values in specific organs. Most fish that possess a Root effect can regulate red blood cell pH during an acidosis, but the combination of ocean acidification and strenuous exercise may overcome their regulatory capacity. Inability to regulate red blood cell pH during exposure to low pH water reduces the oxygen extraction capacity of fish (and thus their MMR and AS). Few fish species have been studied in detail to date, especially among deep-sea fish (Seibel and Walsh, 2003).

According to the "thermal limitation of oxygen delivery" hypothesis explained above, ocean acidification should result in a lower aerobic scope and a narrowing of the acceptable temperature range. Mechanisms involved in maintaining acid-base equilibrium, CO_2 excretion and O_2 transport at low pH involve an energetic cost. This increases SMR. If these mechanisms are not entirely successful in maintaining oxygen extraction capacity, MMR is lower. Together, these result in a smaller aerobic scope and may also reduce the thermal window of a species (Fig. 2–2) (Pörtner and Farrell, 2008). A reduced scope means lower maximum performance.

Many studies suggest that marine and freshwater fish can maintain a large AS at pH values in the 7–8 range, meaning that they are unlikely to be impacted upon by hypoxia in the coming century, considering that pH in the Atlantic LAB is predicted to be ~ 8 in surface water, and ~7.9 in deep water for 2060–2070 (see above) and that the global prediction for 2100 is pH of ~7.75 (see above). In freshwater salmonids, swimming performance is still close to maximum at pH = 6, but lower pH values reduced maximum sustainable swimming speed because it lowers the oxygen carrying capacity of the blood (Randall and Brauner, 1991). Hatchery-reared (freshwater) salmonids can tolerate a pH of 5.0 indefinitely (Fromm, 1980). It is only when the acid-base regulation mechanisms fail that blood becomes acidic and the oxygen-carrying capacity drops (Fromm, 1980). A marine fish, the spotted wolffish (*Anarhichas minor*, 16 g juveniles) has been tested at pH values 8.10, 6.98, 6.71 and 6.45 (Foss et al., 2003). Growth rate was significantly reduced only at the lowest pH, 6.45, indicating a high tolerance of juvenile spotted wolffish for low pH. However, calcareous precipitates, i.e., nephrocalcinosis, were observed at low incidence in all groups, but at a significantly greater incidence in the groups exposed to the two lowest pH treatments. Although this condition rarely kills fish and can be reversible (Foss et al., 2003), kidney function is likely impaired. But very low pH levels were required to reduce growth or increase the incidence and severity of nephrocalcinosis.

The contradictory responses observed between and within taxonomic groups enhance the importance of species-specific life history and physiology characteristics and the need to understand underlying mechanisms to achieve better predictive capabilities. The interaction between acidification and ontogeny also requires more study. The general trend seems to be that larval and juveniles stages are generally more vulnerable to hypercapnia alone, but the hypercapnia with elevated temperature would likely favour smaller individual body size (Pörtner and Farrell, 2008).

As noted previously, acidification in surface water will be caused uniquely by the increased diffusion of CO_2 from the atmosphere. But where the water column is stratified and deep water is not in contact with the atmosphere, hypoxic conditions develop (oxygen is used for respiration but not replaced). This respiration produces CO_2 and renders deep water more acidic than surface water (Burnett, 1997; Melzner et al., 2012). As a result, pH of deep water in the Laurentian Channel, in the St. Lawrence Estuary, is already at pH ~7.6–7.64, and pH might reach 7.4 in 2060–2070. Fish and invertebrates living in deep channels of the GSL, and maybe also on the slopes in SS-GM, will face two (hypoxia and acidification) or three (elevated temperature added to the other two) stressors at once (Burnett, 1997; Pörtner, 2008). The interaction hypoxia + hypercapnia is not necessary deleterious: in the blue crab (*Callinectes sapidus*), severe hypoxia (but not moderate hypoxia) accompanied by increased PCO_2 results in an increase in plasma pH, despite the lower pH of water. This increases the oxygen affinity of the crab's haemocyanin. The mechanism for the increase in plasma pH is unknown (reviewed in Burnett, 1997). The interaction of these stressors is likely to worsen the effect of any single stressor for the majority of the species found in the deep channels of the GSL.

Acidification is probably the most complex of the abiotic factors reviewed here. It can be a masking factor by imposing costs of acid-base regulation and increasing the cost of depositing and maintaining the exoskeletton, and it can be a limiting factor if it reduces the oxygen-carrying capacity of the blood.

2.5 SALINITY

Salinity was classified as a 'masking factor' by Fry (1971; Peck and van der Veer, 2010): masking factors modify the effect of other factors, such as temperature and dissolved oxygen, or prevent the effect of other factors, by forcing organisms to invest (channel) energy to respond to the masking factor. In this case, changes in salinity influence the cost of osmoregulation.

The body fluids of the vast majority of marine teleost fishes are quite different in osmotic strength and ionic composition from that of the surrounding water (Jobling, 1995). Thus, the osmolality of seawater is within the range 800–1200 mOsm kg^{-1}, whereas that of most marine fish falls within the range 370–480 mOsm kg^{-1}, or approximately one third that of full-strength seawater (Jobling, 1995; Árnason et al., 2013). If fishes were impermeable, any difference between internal and external osmotic strength would be inconsequential, but fishes are not impermeable. Their respiratory membranes, in particular, are very permeable because they must allow the exchange of O_2 and CO_2 with water. Because of this, there is a tendency for water to move from marine teleost fishes to the surrounding environment, and for sodium and chloride, but also other ions, to move into fishes.

Such gradients exist because marine fishes can regulate the osmolality of their extracellular and intracellular fluids using ion pumps. These pumps also allow fishes to have a different ion composition than seawater both in extracellular fluids, and within cells. Active transport requires energy. This cost is included in the standard metabolic rate (Fry, 1971).

Because they are hypo-osmotic in seawater, teleost fishes must drink seawater to compensate for the loss of water through their respiratory membranes. By drinking seawater, fishes also ingest salts, which must be excreted at a higher concentration than that of the water they drank (Schmidt-Nielsen, 1990; Jobling, 1995; Árnason et al., 2013). Monovalent ions are secreted by active transport in special cells, called chloride cells, located on the gills, whereas divalent ions are secreted by the kidneys (Jobling, 1995; Árnason et al., 2013).

On the contrary, hagfish, elasmobranchs and most marine invertebrates are iso-osmotic with the surrounding water (Schmidt-Nielsen, 1990). This means that unlike teleost fishes, water does not have a tendency to leave their body. They still need to perform ion regulation, however, because the concentrations of many ions differ between seawater and their internal fluids (Schmidt-Nielsen, 1990). Further, elasmobranchs are different from the other organisms that are iso-osmotic: their ion concentrations are lower than that of seawater, like teleost fishes, but they have elevated levels of urea in their body fluids to raise osmotic concentration (Schmidt-Nielsen, 1990).

Water breathers differ in their ability to adjust to changes in salinity. Species with a very narrow salinity tolerance are stenohaline, whereas those with a broad salinity range are euryhaline. Stenohaline species are found on ocean shelves and in deeper waters, where salinity is very stable (32 to 35). Species inhabiting smaller estuaries with salinity gradients have to be euryhaline.

There are two ways for marine animals to adapt to changing salinity. Most marine invertebrates, such as starfish and oysters, are passive oxyconformers, which adapt their ionic concentrations to that of the water (seawater or brackish estuarine water). Most fish are active oxyregulators, and attempt to maintain the same internal ionic concentrations regardless of the surrounding water salinity. In the long run, active oxyregulators can adapt to more important (and long-lasting) changes in salinity (Schmidt-Nielsen, 1990).

As stated earlier, most marine teleost fishes are hypo-osmotic in full-strength seawater. They are iso-osmotic in water that is about one-third full strength. Many fishes have better growth rates at salinities approaching iso-osmotic conditions, presumably because of the lower cost of osmoregulation, and therefore more of the ingested energy is available for growth (Boeuf and Payan, 2001; Árnason et al., 2013). It is also possible that salinity influences food conversion and/or conversion (Boeuf and Payan, 2001). However, other species have similar growth rates within a wide range of salinities, such as the spotted wolffish (salinities of 12 to 34, Foss et al., 2001). The faster growth rate common, but not universal, at intermediate salinities may be one reason the juveniles of many species select estuaries (Boeuf and Payan, 2001).

Marine teleost fishes become hyper-osmotic at salinities lower than about 12 (one third of full seawater salinity). Without regulation, water would move in the cells and disrupt cell volume. Fishes could pump ions in or out of the cells to prevent changes in cell volume, but this would disrupt cell metabolism. Instead, amino acids whose roles are not influenced by their concentrations, such as glycine, serine, beta-alanine and others, move out of cells to equilibrate osmolality and maintain cell volume (Schmidt-Nielsen, 1990). Another problem of marine fishes moving into brackish water is that solutes tend to leave the body because of the lower solute concentration of the water. Ion pumps are required to maintain the higher ion concentrations within the fish.

In summary, the small changes in salinity projected for 2020–2030 or even for 2060–2070 (Chabot and Gilbert, 2013; Loder et al., 2013) should be within the tolerance range of even stenohaline species, and not be a concern at all for euryhaline species, in metabolic terms.

There can be non-osmoregulatory impacts of changes in salinity on water breathers of the Atlantic LAB. Changes in salinity can affect blood oxygen transport capacity, oxygen delivery to tissues, muscle contractility and maximum sustainable swimming speed in coho salmon *Oncorhynchus kisutch* (Randall and Brauner, 1991), and probably other species as well. Changes in salinity away from the optimal range for a species could therefore act as hypoxia and acidification in reducing thermal tolerance (Fig. 2–2). These effects are usually limited to the acclimation period (Randall and Brauner, 1991). Even after acclimation, salinity can act synergistically to increase the impact of other stressors (temperature, hypoxia, low pH). For example, low salinity raises the susceptibility of the oyster *Crassostrea virginica* to low pH (Dickinson et al., 2012).

There could be indirect effects of salinity changes through altered food supply for the early life stages of commercial fish and crustacean species, which often rely heavily on copepod prey (see Chabot et al., 2013). The relative abundance of the constituent species of the copepod community has been shown to vary with salinity (Vuorinen et al., 1998; Daase et al., 2007). However, the changes in salinity projected for surface waters of the Atlantic LAB in 2060–2070 are small (0.1–1 unit, Loder et al., 2013).

Salinity is closely tied to water density. The position of eggs and small larvae in the water column is controlled by their density relative to that of the surrounding water (e.g., Nissling and Westin, 1991Atlantic cod; Stene et al., 1999, Greenland halibut; Ouellet et al., 2007, Northern shrimp *Pandalus borealis*). Changes in salinity could change the position of eggs in the water column compared with today's conditions. As stated earlier, changes in salinity are expected to be small.

Salinity influences the solubility of oxygen in seawater. As stated earlier, the small decrease in salinity (both surface and deep water) should result in a small increase in the solubility of oxygen. However, the decrease in oxygen solubility caused by the warming of the water will be of greater amplitude.

2.6 CONCLUSION

Physiologists have gathered a vast body of knowledge on how ectothermic species react to changes in abiotic variables. Four variables stand out because of their strong influence on the survival and productivity of fishes and marine invertebrates: temperature, dissolved oxygen, pH/acidification and salinity. The main mechanisms by which these variables impact on ectothermic species were summarized in this document. All four variables are expected to change with climate warming, as described by Loder et al. (2013) and summarized by Chabot and Gilbert (2013).

A good deal of information is already available in the physiological literature to infer how marine fishes and invertebrates may be impacted upon by climate change. It is possible to explore the literature to obtain a first assessment of the susceptibility of commercially important species. Chabot et al. (2013) combined such a literature review with the principles described here and what is expected to happen with these four abiotic variables in 2020–2030 and in 2060–2070. The result is a series of synopses, one for each of the two periods of interest, describing how nine species of fish and three of crustaceans of the Atlantic LAB are expected to be impacted upon by climate change.

2.7 ACKNOWLEDGEMENTS

This review is part of the contribution of D. Chabot to Working Group 1 of the COST action FA1004 Conservation Physiology of Marine Fishes.

2.8 REFERENCES

Árnason, T., Magnadóttir, B., Björnsson, B., Steinarsson, A. and Björnsson, B.T. 2013. Effects of salinity and temperature on growth, plasma ions, cortisol and immune parameters of juvenile Atlantic cod (*Gadus morhua*). Aquaculture, **380–383**(0): 70-79. doi:10.1016/j.aquaculture.2012.11.036.

Bejda, A.J., Phelan, B.A. and Studholme, A.L. 1992. The effect of dissolved oxygen on the growth of young-of-the-year winter flounder, *Pseudopleuronectes americanus*. Environ. Biol. Fish., **34**(3): 321-321.

Bell, G.W. and Eggleston, D.B. 2005. Species-specific avoidance responses by blue crabs and fish to chronic and episodic hypoxia. Mar. Biol., **146**(4): 761-770.

Bell, G.W., Eggleston, D.B. and Wolcott, T.G. 2003. Behavioral responses of free-ranging blue crabs to episodic hypoxia. II. Feeding. Mar. Ecol. Prog. Ser., **259**: 227-235.

Bickler, P.E. and Buck, L.T. 2007. Hypoxia tolerance in reptiles, amphibians, and fishes: life with variable oxygen availability. Annu. Rev. Physiol., **69**: 145-170.

Björnsson, B., Steinarsson, A. and Árnason, T. 2007. Growth model for Atlantic cod (*Gadus morhua*): effects of temperature and body weight on growth rate. Aquaculture, **271**(1-4): 216-226.

Boeuf, G. and Payan, P. 2001. How should salinity influence fish growth? Comp. Biochem. Physiol. C, **130**: 411-423.

Bourque, M. 2009. Variation spatio-temporelle de la macrofaune endobenthique dans la zone profonde du Saint-Laurent (Québec, Canada) en relation avec les conditions environnementales. M. Sc. thesis. Université du Québec à Rimouski, Rimouski, QC, Canada.

Brauner, C.J. and Randall, D.J. 1998. The linkage between oxygen and carbon dioxide transport *In* Fish respiration. *Edited by* S.F. Perry and C.B. Tufts. Fish physiology Academic Press, San Diego, CA, USA., pp. 283-319.

Breitburg, D.L., Hondorp, D.W., Davias, L.A. and Diaz, R.J. 2009. Hypoxia, nitrogen, and fisheries: integrating effects across local and global landscapes. Annu. Rev. Mar. Sci., **1**: 329-349.

Brett, J.R. and Groves, T.D.D. 1979. Physiological energetics *In* Bioenergetics and growth(VIII). *Edited by* W.S. Hoar, D.J. Randall and J.R. Brett. Academic Press, New York., pp. 279-352.

Buentello, J.A., Gatlin III, D.M. and Neill, W.H. 2000. Effects of water temperature and dissolved oxygen on daily feed consumption, feed utilization and growth of channel catfish (*Ictalurus punctatus*). Aquaculture, **182**(3–4): 339-352. doi:10.1016/S0044-8486(99)00274-4.

Burnett, L.E. 1997. The challenges of living in hypoxic and hypercapnic aquatic environments. Amer. Zool., **37**(6): 633-640.

Chabot, D. and Claireaux, G. 2008. Environmental hypoxia as a metabolic constraint on fish: the case of Atlantic cod, *Gadus morhua*. Mar. Pollut. Bull., **57**(6-12): 287-294.

Chabot, D. and Dutil, J.-D. 1999. Reduced growth of Atlantic cod in non-lethal hypoxic conditions. J. Fish Biol., **55**(3): 472-491.

Chabot, D. and Gilbert, D. 2013. Description of the Atlantic Large Aquatic Basin as a habitat for marine fish and invertebrates, pp. 1-15 *In* Climate change impacts, vulnerabilities and opportunities analysis of the marine Atlantic Basin. *Edited by* N.L. Shackell, B.J.W. Greenan, P. Pepin, D. Chabot, A. Warburton. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

Chabot, D., Guénette, G. and Stortini, C. 2013. A review of the physiological susceptibility of commercial species of fish and crustaceans of the Nortwest Atlantic to changes in water temperature, dissolved oxygen, pH and salinity, pp. 83-168 *In* Climate change impacts, vulnerabilities and opportunities analysis of the marine Atlantic Basin. *Edited by* N.L. Shackell, B.J.W. Greenan, P. Pepin, D. Chabot, A. Warburton. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

Childress, J.J. and Seibel, B.A. 1998. Life at stable low oxygen levels: adaptations of animals to oceanic oxygen minimum layers. J. Exp. Biol., **201**(8): 1223-1232.

Christen, F. 2012. Le métabolisme postprandial comme possible explication de la variabilité inter-individuelle au niveau de la croissance chez les poissons & Influence de l'hypoxie sur le métabolisme postprandial, avec comme modèle : le loup tacheté (*Anarhichas minor*). Master thesis. Université de Bretagne Occidentale, U.F.R. Sciences Techniques.

Claireaux, G. and Lagardère, J.-P. 1999. Influence of temperature, oxygen and salinity on the metabolism of the European sea bass. J. Sea Res., **42**(2): 157-168.

Claireaux, G., Webber, D., Kerr, S. and Boutilier, R. 1995. Physiology and behaviour of free-swimming Atlantic cod (*Gadus morhua*) facing fluctuating salinity and oxygenation conditions. J. Exp. Biol., **198**(1): 61.

Claireaux, G., Webber, D.M., Lagardère, J.P. and Kerr, S.R. 2000. Influence of water temperature and oxygenation on the aerobic metabolic scope of Atlantic cod (*Gadus morhua*). J. Sea Res., **44**(3-4): 257-265.

Clark, T.D., Sandblom, E. and Jutfelt, F. 2013. Aerobic scope measurements of fishes in an era of climate change: respirometry, relevance and recommendations. J. Exp. Biol., **216**(Pt 15): 2771-2782. doi:10.1242/jeb.084251.

Cloern, J.E. 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser., **210**(2001): 223-253.

Crowder, L.B. and Magnuson, J.J. 1983. Cost benefit analysis of temperature and food resource use: a synthesis with an example from the fishes *In* Behavioral energetics: The cost of survival in vertebrates. *Edited by* W.P. Aspey and S.I. Lustick. Ohio State University Press, Columbus, OH., pp. 189-221.

Daase, M., Vik, .O., Bagoien, E., Stenseth, C. and Eiane, K. 2007. The influence of advection on *Calanus* near Svalbard: statistical relations between salinity, temperature and copepod abundance. J. Plankton Res., **29**(10): 903-911. doi:10.1093/plankt/fbm068.

Das, T. and Stickle, W.B. 1994. Detection and avoidance of hypoxic water by juvenile *Callinectes sapidus* and *C. similis*. Mar. Biol., **120**(4): 593-600.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Board Can., **32**: 2295-2332.

Descroix, A., Harvey, M., Roy, S. and Galbraith, P.S. 2005. Macrozooplankton community patterns driven by water circulation in the St. Lawrence marine system, Canada. Mar. Ecol. Prog. Ser., **302**: 103-119.

Despatie, S.-P., Castonguay, M., Chabot, D. and Audet, C. 2001. Final thermal preferendum of Atlantic cod: effect of food ration. Trans. Am. Fish. Soc., **130**: 263-275.

Diaz, R.J. 2001. Overview of hypoxia around the world. J Environ Qual, **30**(2): 275-281.

Diaz, R.J. and Rosenberg, R. 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. Oceanogr. Mar. Biol. Annu. Rev., **33**: 245-303.

Diaz, R.J. and Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. Science, **321**(5891): 926-929. doi:10.1126/science.1156401.

Dickinson, G.H., Ivanina, A.V., Matoo, O.B., Pörtner, H.O., Lannig, G., Bock, C., Beniash, E. and Sokolova, I.M. 2012. Interactive effects of salinity and elevated CO2 levels on juvenile eastern oysters, *Crassostrea virginica*. J. Exp. Biol., **215**(1): 29-43.

Diez, J.M. and Davenport, J. 1990. Energy exchange between the yolk and embryo of dogfish (*Scyliorhinus canicula* L.) eggs held under normoxic, hypoxic and transient anoxic conditions. Comp. Biochem. Physiol. B, **96**(4): 825-830. doi:10.1016/0305-0491(90)90239-P.

Dupont-Prinet, A., Vagner, M., Chabot, D. and Audet, C. 2013. Impact of hypoxia on the metabolism of Greenland halibut (*Reinhardtius hippoglossoides*). Can. J. Fish. Aquat. Sc., **70**: 461-469.

Dutil, J.-, Sylvestre, E.-, Gamache, L., Larocque, R. and Guderley, H. 2007. Burst-coast use, swimming performance, and metabolism of Atlantic cod (*Gadus morhua*) in sub-lethal hypoxic conditions. J. Fish Biol., **71**: 1-13.

Dyer, M.F., Pope, J.G., Fry, P.D., Law, R.J. and Portmann, J.E. 1983. Changes in fish and benthos catches off the Danish cost in September 1981. J. Mar. Biol. Ass. U. K., **63**(4): 767-775.

Eby, L.A. and Crowder, L.B. 2002. Hypoxia-based habitat compression in the Neuse River Estuary: context-dependent shifts in behavioral avoidance thresholds. Can. J. Fish. Aquat. Sc., **59**(6): 952-965. doi:10.1139/F02-067.

Eby, L.A., Crowder, L.B., McClellan, C.M., Peterson, C.H. and Powers, M.J. 2005. Habitat degradation from intermittent hypoxia: impacts on demersal fishes. Mar. Ecol. Prog. Ser., **291**: 249-262.

Ekau, W., Auel, H., Pörtner, H. and Gilbert, D. 2010. Impacts of hypoxia on the structure and processes in pelagic communities (zooplankton, macro-invertebrates and fish). Biogeosciences, **7**(5): 1669-1699. doi:10.5194/bg-7-1669-2010.

Eriksson, S.P. and Baden, S.P. 1997. Behaviour and tolerance to hypoxia in juvenile Norway lobster (*Nephrops norvegicus*) of different ages. Mar. Biol., **128**(1): 49-54.

Fabry, V.J., Seibel, B.A., Feely, R.A. and Orr, J.C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES J. Mar. Sci., **65**(3): 414-432.

Foss, A., Evensen, T.H., Imsland, A.K. and Øiestad, V. 2001. Effects of reduced salinities on growth, food conversion efficiency and osmoregulatory status in the spotted wolffish. J. Fish Biol., **59**(2): 416-426.

Foss, A., Evensen, T.H. and Øiestad, V. 2002. Effects of hypoxia and hyperoxia on growth and food conversion efficiency in the spotted wolffish *Anarhichas minor* (Olafsen). Aquacult. Res., **33**(6): 437-444.

Foss, A., Røsnes, B.A. and Øiestad, V. 2003. Graded environmental hypercapnia in juvenile spotted wolffish (*Anarhichas mino*r Olafsen): effects on growth, food conversion efficiency and nephrocalcinosis. Aquaculture, **220**(1-4): 607-617.

Frappell, P.B. and Butler, P.J. 2004. Minimal metabolic rate, what it is, its usefulness, and its relationship to the evolution of endothermy: A brief synopsis. Physiol. Biochem. Zool., **77**(6): 865-868.

Fromm, P.O. 1980. A review of some physiological and toxicological responses of freshwater fish to acid stress. Environ. Biol. Fish., **5**(1): 79-93. doi:10.1007/BF00000954.

Fry, F.E.J. 1947. Effects of the environment on animal activity. Publication of the Ontario Fisheries Research Laboratory 68: 1-62 p.

Fry, F.E.J. 1971. The effect of environmental factors on the physiology of fish *In* Fish physiology, vol. 6. *Edited by* W.S. Hoar and D.J. Randall. Academic Press, New York., pp. 1-98.

Fry, F.E.J. and Hart, J.S. 1948. The relation of temperature to oxygen consumption in the goldfish. Biol. Bull., **94**(1): 66-77.

Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Brickman, D., Pettigrew, B., Devine, L., Gosselin, A., Pettipas, R.G. and Lafleur, C. 2012. Physical oceanographic conditions in the Gulf of St. Lawrence in 2011. Can. Sc. Adv. Secr. Res. Doc. 2012/023: iii + 85 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_023-eng.pdf

García, H.E. and Gordon, L.I. 1992. Oxygen solubility in seawater: better fitting equations. Limnol. Oceanogr., **37**(6): 1307-1312.

Gilbert, D., Chabot, D., Archambault, P., Rondeau, B. and Hébert, S. 2007. Appauvrissement en oxygène dans les eaux profondes du Saint-Laurent marin — Causes possibles et impacts écologiques. Nat. Can., **131**(1): 67-75.

Gilbert, D., Sundby, B., Gobeil, C., Mucci, A. and Tremblay, G.- 2005. A seventy-two year record of diminishing deep-water oxygen in the St. Lawrence estuary: the northwest Atlantic connection. Limnol. Oceanogr., **50**(5): 1654-1666.

Gray, J.S., Wu, R.S.-S. and Or, Y.Y. 2002. Effects of hypoxia and organic enrichment on the coastal marine environment. Mar. Ecol. Prog. Ser., **238**(249-279).

Haselmair, A., Stachowitsch, M., Zuschin, M. and Riedel, B. 2010. Behaviour and mortality of benthic crustaceans in response to experimentally induced hypoxia and anoxia in situ. Mar. Ecol. Prog. Ser., **414**: 195-208.

Herbert, N. and Steffensen, J. 2005. The response of Atlantic cod, *Gadus morhua*, to progressive hypoxia: fish swimming speed and physiological stress. Mar. Biol., **147**: 1403-1412.

Hofmann, A.F., Peltzer, E.T., Walz, P.M. and Brewer, P.G. 2011. Hypoxia by degrees: Establishing definitions for a changing ocean. Deep-Sea Research I, **58**: 1212-1226.

Hoos, L.M. 1973. A study of the benthos of an anoxic marine basin and factors affecting its distribution. M. Sc. thesis. Dalhousie University, Halifax, NS. 149 pp.

Hulbert, A.J. and Else, P.L. 2004. Basal metabolic rate: History, composition, regulation, and usefulness. Physiol. Biochem. Zool., **77**(6): 869-876.

Jobling, M. 1981. The influences of feeding on the metabolic rate of fishes: a short review. J. Fish Biol., **18**(4): 385-400.

Jobling, M. 1995. Environ. Biol. Fish. Chapman & Hall. xii + 455 p.

Jordan, A.D. and Steffensen, J.F. 2007. Effects of ration size and hypoxia upon specific dynamic action (SDA) in the cod. Physiol. Biochem. Zool., **80**(2): 178-185.

Kemp, W.M., Testa, J.M., Conley, D.J., Gilbert, D. and Hagy, J.D. 2009. Temporal responses of coastal hypoxia to nutrient loading and physical controls. Biogeosciences, **6**(12): 2985-3008.

Kolar, C.S. and Rahel, F.J. 1993. Interaction of a biotic factor (predator presence) and an abiotic factor (low oxygen) as an influence on benthic invertebrate communities. Oecologia. **95**(2): 210-219.

Kramer, D.L. 1987. Dissolved oxygen and fish behavior. Environ. Biol. Fish., **18**(2): 81-92.

Kristiansen, T. 2001. Optimal selection of temperature areas by juvenile cod (*Gadus morhua* L.) in the Barents Sea modelled by dynamic optimisation. ICES J. Mar. Sci., **58**(1): 172-182. doi:10.1006/jmsc.2000.1000.

Kroeker, K.J., Kordas, R.L., Crim, R.N. and Singh, G.G. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol. Lett., **13**(11): 1419-1434.

Landry, C.A., Steele, S.L., Manning, S. and Cheek, A.O. 2007. Long term hypoxia suppresses reproductive capacity in the estuarine fish, *Fundulus grandis.* Comp. Biochem. Physiol. A, **148**(2): 317-323. doi:10.1016/j.cbpa.2007.04.023.

Lefrançois, C. and Claireaux, G. 2003. Influence of ambient oxygenation and temperature on metabolic scope and scope for heart rate in the common sole Solea solea. Mar. Ecol. Prog. Ser., **259**: 273-284.

Levin, L.A., Ekau, W., Gooday, A.J., Jorissen, F., Middelburg, J.J., Naqvi, W., Neira, C., Rabalais, N.N. and Zhang, J. 2009. Effects of natural and human-induced hypoxia on coastal benthos. Biogeosciences, **6**: 2063-2098.

Lim, H.-S., Diaz, R.J., Hong, J.-S. and Schaffner, L.C. 2006. Hypoxia and benthic community recovery in Korean coastal waters. Mar. Pollut. Bull., **52**(11): 1517-1526.

Loder, J.W., Chassé, J., Galbraith, P., Han, D., Lavoie, D., and others. 2013. Summary of climate change trends and projections for the Atlantic Large Aquatic Basin off Canada. Can. Techn. Rep. Fish. Aquat. Sci. 3051 (under revision).

Mac, M.J. 1985. Effects of ration size on preferred temperature of lake charr *Salvelinus namaycush*. Environ. Biol. Fish., **14**(2-3): 227-231.

Marcus, N.H., Richmond, C., Sedlacek, C., Miller, G.A. and Oppert, C. 2004. Impact of hypoxia on the survival, egg production and population dynamics of *Acartia tonsa* Dana. J. Exp. Mar. Biol. Ecol., **301**(2): 111-128. doi:10.1016/j.jembe.2003.09.016.

McNatt, R.A. and Rice, J.A. 2004. Hypoxia-induced growth rate reduction in two juvenile estuary-dependent fishes. J. Exp. Mar. Biol. Ecol., **311**(1): 147-156.

Mejri, S., Tremblay, R., Lambert, Y. and Audet, C. 2012. Influence of different levels of dissolved oxygen on the success of Greenland halibut (*Reinhardtius hippoglossoides*) egg hatching and embryonic development. Mar. Biol., **159**(8): 1693-1701. doi:10.1007/s00227-012-1957-y.

Melzner, F., Göbel, S., Langenbuch, M., Gutowska, M.A., Pörtner, H.O. and Lucassen, M. 2009. Swimming performance in Atlantic cod (*Gadus morhua*) following long-term (4–12 months) acclimation to elevated seawater P_{CO2}. Aquat. Toxicol., **92**(1): 30-37. doi:10.1016/j.aquatox.2008.12.011.

Melzner, F., Thomsen, J., Koeve, W., Oschlies, A., Gutowska, M.A., Bange, H.W., Hansen, H.P. and Körtzinger, A. 2012. Future ocean acidification will be amplified by hypoxia in coastal habitats. Mar. Biol., **160**: 1875-1888. doi:10.1007/s00227-012-1954-1.

Michaelidis, B., Ouzounis, C., Paleras, A. and Pörtner, H.O. 2005. Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels *Mytilus galloprovincialis*. Mar. Ecol. Prog. Ser., **293**(2): 109-118.

Miller, D., Poucher, S. and Coiro, L. 2002. Determination of lethal dissolved oxygen levels for selected marine and estuarine fishes, crustaceans, and a bivalve. Mar. Biol., **140**(2): 287-296. doi:10.1007/s002270100702.

Montagna, P.A. and Ritter, C. 2006. Direct and indirect effects of hypoxia on benthos in Corpus Christi Bay, Texas, USA. J. Exp. Mar. Biol. Ecol., **330**(1): 119-131.

Morgan, M.J. 1993. Ration level and temperature preference of American plaice. Mar. Freshwat. Behav. Physiol., **24**(2): 117-122. doi:10.1080/10236249309378884.

Nelson, J.A. and Chabot, D. 2011. Energy Consumption: Metabolism (general) *In* Encyclopedia of fish physiology: from genome to environment. *Edited by* A.P. Farrell. Academic Press., pp. 1566-1572.

Nienhuis, S., Palmer, A.R. and Harley, C.D. 2010. Elevated CO_2 affects shell dissolution rate but not calcification rate in a marine snail. Proceedings of the Royal Society B: Biological Sciences, **277**(1693): 2553-2558.

Nissling, A. and Westin, L. 1991. Egg buoyancy of Baltic cod (*Gadus morhua*) and its implications for cod stock fluctuations in the Baltic. Mar. Biol., **111**(1): 33-35.

Ouellet, P., Savard, L. and Larouche, P. 2007. Spring oceanographic conditions and northern shrimp *Pandalus borealis* recruitment success in the north-western Gulf of St. Lawrence. Mar. Ecol. Prog. Ser., **339**: 229-241.

Peck, M.A. and van der Veer, H.W. 2010. Ecophysiology *In* Resolving climate impacts on fish stocks. *Edited by* A.D. Rijnsdorp, M.A. Peck, G.H. Engelhard, C. Möllmann and J.K. Pinnegar. ICES Cooperative Research Report ICES, Copenhagen, Denmark., pp. 21-33.

Pecl, G.T. and Jackson, G.D. 2008. The potential impacts of climate change on inshore squid: biology, ecology and fisheries. Rev. Fish Biol. Fish., **18**(4): 373-385. doi:10.1007/s11160-007-9077-3.

Pelster, B. and Randall, D. 1998. 4 The Physiology of the Root Effect *In* Fish respiration. *Edited by* S.F. Perry and C.B. Tufts. Fish physiology Academic Press, San Diego, CA, USA., pp. 113-139.

Perry, S.F. and McDonald, G. 1993. Gas exchange *In* The physiology of fishes. *Edited by* D.H. Evans. CRC Marine science series CRC-Press, Boca Raton, Florida, US., pp. 251-278.

Petersen, J.K. and Pihl, L. 1995. Responses to hypoxia of plaice, *Pleuronectes platessa*, and dab, *Limanda limanda*, in the south-east Kattegat: distribution and growth. Environ. Biol. Fish., **43**(3): 311-321.

Pihl, L. 1994. Changes in the diet of demersal fish due to eutrophication-induced hypoxia in the Kattegat, Sweden. Can. J. Fish. Aquat. Sc., **51**: 321-336.

Plante, S., Chabot, D. and Dutil, J.D. 1998. Hypoxia tolerance in Atlantic cod. J. Fish Biol., **53**(6): 1342-1356.

Plourde, S., Dodson, J.J., Runge, J.A. and Therriault, J.-C. 2002. Spatial and temporal variations in copepod community structure in the lower St. Lawrence Estuary, Canada. Mar. Ecol. Prog. Ser., **230**: 211-224.

Pollock, M.S., Clarke, L.M.J. and Dubé, M.G. 2007. The effects of hypoxia on fishes: from ecological relevance to physiological effects. Environmental Reviews, **15**(NA): 1-14.

Pörtner, H.O. 2001. Climate change and temperature-dependent biogeography: oxygen limitation of thermal tolerance in animals. Naturwissenschaften, **88**(4): 137-146.

Pörtner, H.O. 2002. Climate variations and the physiological basis of temperature dependent biogeography: systemic to molecular hierarchy of thermal tolerance in animals. Comp. Biochem. Physiol. A, **132**(4): 739-761.

Pörtner, H.O. 2008. Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. Mar. Ecol. Prog. Ser., **373**: 203-217. doi:10.3354/meps07768.

Pörtner, H.O. and Farrell, A.P. 2008. Physiology and climate change. Science, **322**: 690-692.

Pörtner, H.O. and Knust, R. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science, **315**(5808): 95-97. doi:10.1126/science.1135471.

Pörtner, H.O. and Peck, M.A. 2010. Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J. Fish Biol., **77**(8): 1745-1779. doi:10.1111/j.1095-8649.2010.02783.x.

Pörtner, H.O., Berdal, B., Blust, R., Brix, O., Colosimo, A., De Wachter, B., Giuliani, A., Johansen, T., Fischer, T. and Knust, R. 2001. Climate induced temperature effects on growth performance, fecundity and recruitment in marine fish: developing a hypothesis for cause and effect relationships in Atlantic cod (*Gadus* *morhua*) and common eelpout (*Zoarces viviparus*). Cont. Shelf Res., **21**(18-19): 1975-1997.

Pörtner, H.O., Bock, C., Knust, R., Lannig, G., Lucassen, M., Mark, F.C. and Sartoris, F.J. 2008. Cod and climate in a latitudinal cline: physiological analyses of climate effects in marine fishes. Climate Reseach, **37**(2-3): 253-270. doi:10.3354/cr00766.

Purcell, J.E., Uye, S.-I. and Lo, W.-T. 2007. Anthropogenic causes of jellyfish blooms and their direct consequences for humans: a review. Mar. Ecol. Prog. Ser., **350**: 153-174.

Rabalais, N.N. 2009. Hypoxia *In* Encyclopedia of ocean sciences. *Edited by* J.H. Steele, K.K. Turekian and S.A. Thorpe. Elsevier., pp. 3868-3877.

Rabalais, N.N., Turner, R.E. and Wiseman Jr, W.J. 2002. Gulf of Mexico hypoxia, AKA" The dead zone". Annu. Rev. Ecol. Syst.,: 235-263.

Rabalais, N.N., Turner, R.E., Díaz, R.J. and Justić, D. 2009. Global change and eutrophication of coastal waters. ICES J. Mar. Sci., **66**(7): 1528.

Rabalais, N.N., Diaz, R.J., Levin, L.A., Turner, R.E., Gilbert, D. and Zhang, J. 2010. Dynamics and distribution of natural and human-caused hypoxia. Biogeosciences, **7**(2): 585-619.

Randall, D. and Brauner, C. 1991. Effects of environmental factors on exercise in fish. J. Exp. Biol., **160**(1): 113-126.

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C. and Watson, A. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. The Royal Society Policy Document 12/05: viii + 60 p. Available from http://dge.stanford.edu/labs/caldeiralab/Caldeira%20downloads/RoyalSociety_OceanAcidification.pdf

Ries, J.B., Cohen, A.L. and McCorkle, D.C. 2009. Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. Geology, **37**(12): 1131-1134.

Rosenberg, R. 1980. Effect of oxygen deficiency on benthic macrofauna in fjords *In* Fjord oceanography. *Edited by* J.H. Freeland, D.M. Farmer and C.D. Levings. Plenum Publ. Corp., New York., pp. 499-514.

Rosenberg, R., Hellman, B. and Johansson, B. 1991. Hypoxic tolerance of marine benthic fauna. Mar. Ecol. Prog. Ser., **79**(1): 127-131.

Scarratt, M., Chabot, D. and Gilbert, D. 2012. Hypoxia in the St. Lawrence Estuary and Gulf *In* Can. Manuscr. Rep. Fish. Aquat. Sci.. *Edited by* H.P. Benoît, J.A. Gagné, C. Savenkoff, P. Ouellet and M.-N. Bourassa. Vol. 2986.., pp. 10-15. Available from http://www.dfo-mpo.gc.ca/Library/345310.pdf

Schmidt-Nielsen, K. 1990. Animal physiology: adaptation and environment. Cambridge University Press. xii + 602 p.

Schurmann, H. and Steffensen, J.F. 1994. Spontaneous swimming activity of Atlantic cod *Gadus morhua* exposed to graded hypoxia at three temperatures. J. Exp. Biol., **197**(1): 129.

Schurmann, H. and Steffensen, J.F. 1997. Effects of temperature, hypoxia and activity on the metabolism of juvenile Atlantic cod. J. Fish Biol., **50**(6): 1166-1180.

Schurmann, H., Claireaux, G. and Chartois, H. 1998. Change in vertical distribution of sea bass (*Dicentrarchus labrax* L.) during a hypoxic episode. Hydrobiologia, **371**: 207-213.

Secor, D.H. and Gunderson, T.E. 1998. Effects of hypoxia and temperature on survival, growth, and respiration of juvenile Atlantic sturgeon, *Acipenser oxyrinchus*. Fish. Bull., **96**(3): 603-613.

Seibel, B.A. 2011. Critical oxygen levels and metabolic suppression in oceanic oxygen minimum zones. J. Exp. Biol., **214**(Pt 2): 326-336. doi:10.1242/jeb.049171.

Seibel, B.A. and Walsh, P.J. 2003. Biological impacts of deep-sea carbon dioxide injection inferred from indices of physiological performance. J. Exp. Biol., **206**(4): 641-650.

Shang, E.H.H., Yu, R.M.K. and Wu, R.S.S. 2006. Hypoxia affects sex differentiation and development, leading to a male-dominated population in zebrafish (*Danio rerio*). Environ. Sci. Technol., **40**(9): 3118-3122.

Stene, A., Gundersen, A.C., Albert, O.T., Nedreaas, K.H. and Solemdal, P. 1999. Early development of Northeast Arctic Greenland halibut (*Reinhardtius hippoglossoides*). J. Northw. Atl. Fish. Sci., **25**: 171-178.

Stevens, G.C. 1989. The latitudinal gradient in geographical range: how so many species coexist in the tropics. American Naturalist,: 240-256.

Stillman, J.H. 2003. Acclimation capacity underlies susceptibility to climate change. Science, **301**(5629): 65.

Sun, H., Li, J., Tang, L. and Yang, Z. 2012. Responses of crucian carp *Carassius auratus* to long-term exposure to nitrite and low dissolved oxygen levels. Biochem. Syst. Ecol., **44**: 224-232. doi:10.1016/j.bse.2012.06.011.

Swain, D.P. 1997. Sex-specific temperature distribution of American plaice (*Hippoglossoides platessoides*) and its relation to age and abundance. Can. J. Fish. Aquat. Sc., **54**(5): 1077-1087.

Swain, D.P. and Kramer, D.L. 1995. Annual variation in temperature selection by Atlantic cod *Gadus morhua* in the southern Gulf of St. Lawrence, Canada, and its relation to population size. Mar. Ecol. Prog. Ser., **116**(1): 11-23.

Swain, D.P. and Morgan, M.J. 2001. Sex-specific temperature distribution in four populations of American plaice *Hippoglossoides platessoides*. Mar. Ecol. Prog. Ser., **212**: 233-246.

Swain, D.P. and Morin, R. 1996. Relationships between geographic distribution and abundance of American plaice (*Hippoglossoides platessoides*) in the southern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sc., **53**(1): 106-119.

Tewksbury, J.J., Huey, R.B. and Deutsch, C.A. 2008. Ecology. Putting the heat on tropical animals. Science, **320**(5881): 1296-1297. doi:10.1126/science.1159328.

The Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment, National Research Council of the National Academies 2010. Ocean acidification. A national strategy to meet the challenges of a changing ocean. The National Academies Press. 175 p.

Thetmeyer, H., Waller, U., Black, K.D., Inselmann, S. and Rosenthal, H. 1999. Growth of European sea bass (*Dicentrarchus labrax* L.) under hypoxic and oscillating oxygen conditions. Aquaculture, **174**(3-4): 355-367.

Thomas, P., Rahman, M.S., Kummer, J.A. and Lawson, S. 2006. Reproductive endocrine dysfunction in Atlantic croaker exposed to hypoxia. Mar. Environ. Res., **62**: S249-S252. doi:10.1016/j.marenvres.2006.04.031.

Tyler, J.A. and Brandt, S.B. 2001. Do spatial models of growth rate potential reflect fish growth in a heterogeneous environment? A comparison of model results. Ecol. Freshw. Fish, **10**(1): 43-56.

Tyson, R.V. and Pearson, T.H. 1991. Modern and ancient continental shelf anoxia: an overview. Geological Society, London, Special Publications, **58**: 1-24. doi:10.1144/GSL.SP.1991.058.01.01.

Uzars, D. 1994. Feeding of cod (*Gadus morhua* callarias L.) in the central Baltic in relation to environmental changes. ICES Mar. Sci. Symp., **198**: 612-623.

Vaquer-Sunyer, R. and Duarte, C.M. 2008. Thresholds of hypoxia for marine biodiversity. Proceedings of the National Academy of Sciences, **105**(40): 15452.

Vuorinen, I., Hänninen, J., Viitasalo, M., Helminen, U. and Kuosa, H. 1998. Proportion of copepod biomass declines with decreasing salinity in the Baltic Sea. ICES J. Mar. Sci., **55**(4): 767-774. doi:10.1006/jmsc.1998.0398.

Wang, T., Lefevre, S., Thanh Huong, D.T., Cong, N. and Bayley, M. 2009. The effects of hypoxia on growth and digestion *In* Hypoxia. *Edited by* J.G. Richards, A.P. Farell and C.J. Brauner. Fish Physiology Academic Press, Amsterdam., pp. 361-396.

Wannamaker, C.M. and Rice, J.A. 2000. Effects of hypoxia on movements and behavior of selected estuarine organisms from the southeastern United States. J. Exp. Mar. Biol. Ecol., **249**(2): 145-163.

Wei, L., Zhang, X., Huang, G. and Li, J. 2009. Effects of limited dissolved oxygen supply on the growth and energy allocation of juvenile Chinese shrimp, *Fenneropenaeus chinensis*. J. World Aquacult. Soc., **40**(4): 483-492.

Whitmore, C.M., Warren, C.E. and Doudoroff, P. 1960. Avoidance reactions of salmonid and centrarchid fishes to low oxygen concentrations. Trans. Am. Fish. Soc., **89**: 17-26.

Wildhaber, M. 2001. The trade-off between food and temperature in the habitat choice of bluegill sunfish. J. Fish Biol., **58**(5): 1476-1478. doi:10.1006/jfbi.2000.1542.

Wildhaber, M.L. and Crowder, L.B. 1990. Testing a bioenergetics-based habitat choice model: bluegill (*Lepomis macrochirus*) responses to food availability and temperature. Can. J. Fish. Aquat. Sc., **47**(9): 1664-1671.

Wildhaber, M.L. and Lamberson, P.J. 2004. Importance of the habitat choice behavior assumed when modeling the effects of food and temperature on fish populations. Ecol. Model., **175**(4): 395-409. doi:10.1016/j.ecolmodel.2003.08.022.

Wu, R.S. 2002. Hypoxia: from molecular responses to ecosystem responses. Mar. Pollut. Bull., **45**(1): 35-45.

Wu, R.S., Zhou, B.S., Randall, D.J., Woo, N.Y. and Lam, P.K. 2003. Aquatic hypoxia is an endocrine disruptor and impairs fish reproduction. Environ. Sci. Technol., **37**(6): 1137-1141.

Zhang, J., Gilbert, D., Gooday, A.J., Levin, L., Naqvi, S.W.A., Middelburg, J.J., Scranton, M., Ekau, W., Pena, A. and Dewitte, B. 2010a. Natural and human-induced hypoxia and consequences for coastal areas: synthesis and future development. Biogeosciences, **7**(5): 1443-1467. doi:10.5194/bg-7-1443-2010.

Zhang, W., Cao, Z.D., Peng, J.L., Chen, B.J. and Fu, S.J. 2010b. The effects of dissolved oxygen level on the metabolic interaction between digestion and locomotion in juvenile southern catfish (*Silurus meridionalis* Chen). Comp. Biochem. Physiol. A, **157**(3): 212-219. doi:10.1016/j.cbpa.2010.06.184.

Chapter 3 Dynamics of lower trophic levels in the western North Atlantic: Past trends and anticipated changes under climate change

P. Pepin* and R.E. Jamieson

Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, 80
East White Hills Road, P. O. Box 5667, St. John's, NL A1C 5X1

*Correspondence: Pierre.Pepin@dfo-mpo.gc.ca

Suggested Citation:
Pepin, P. and R.E., Jamieson. 2013. Dynamics of lower trophic levels in the western North Atlantic: Past trends and anticipated changes under climate change. Ch. 3 (p. 45-82) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

3.1 INTRODUCTION

Fishery production potential of any ecosystem is ultimately determined by total annual primary productivity and the complexity and efficiency of energy transfer from phytoplankton through zooplankton and up to forage fish and other nekton (Ryther, 1969, Ware and Thomson, 2005). Throughout most of the World Ocean, production by large phytoplankton, fuelled by dissolved nutrients (e.g., nitrate, silicate, phosphate, and ammonium), is grazed by metazoan zooplankton, consisting principally of copepods, which are in turn preyed upon by planktivores. An alternate path involves the microbial food web in which primary production by small (< 10 µm) phytoplankton combined with bacterial production fuelled by dissolved organic carbon, produced from the losses from phytoplankton and other trophic levels, is eaten by protozoan microzooplankton that are then consumed by metazoan zooplankton and onto higher trophic levels. The microbial food web is the dominant path of new organic matter production in open ocean basins, but its role in coastal ecosystems can vary seasonally. In areas with sea ice, such as Polar Regions and areas with seasonal ice cover, productivity by under-ice algae, and the associated grazers, can also represent an important determinant of regional productivity. The structure and relative importance of the different pathways of energy transfer in marine ecosystems depends on the physical structure of the water column and how this is affected by seasonal and regional variations atmospheric forcing, mixing and inputs of freshwater.

Climate change is an ongoing process by which changes in atmosphere-ocean coupling caused by increased greenhouse gas concentrations will result in significant changes to terrestrial and aquatic ecosystems. Because any attempt at forecasting future changes in climate can be affected by the strengths and limitations of a model, the International Panel on Climate Change (IPCC) has chosen to summarize predictions based on the average of a suite of models, which overcomes some of the weakness which any one model may have while providing an indication of the range of possible outcomes. Global warming provides a simplified perspective of the dominant effects which climate change will have on the earth, but in aquatic systems important and concurrent changes associated with increased temperatures will include greater inputs of freshwater (from changes in ice-melt and the distribution and timing of precipitation), impeded vertical mixing, changes in circulation, as well as reduced oxygen concentrations and increased acidity of seawater. The severity and rate of change in environmental conditions will not be uniform across the globe. Polar regions are expected to be severely affected by increased global temperatures, partly as a result of the effects on ice-cover for both ocean and land masses, whereas temperate areas will see more moderate changes in at least some environmental variables. Predictions for the latter can have a high degree of uncertainty because they sit at the boundary between tropical and polar biomes. For example, western boundary currents in the northern hemisphere carry heat from subtropical gyres toward polar regions, but the strong density gradients associated with these stream-like flows, variations in atmospheric circulation, and their interaction with southward flowing currents from the Arctic makes predicting changes in their latitudinal position difficult. As a result, any average scenario predictions of physical environmental conditions for the western temperate portions of ocean basins in the northern hemisphere must also consider regional uncertainty in the forecasted changes.

The northwest Atlantic, from the southern Scotian Shelf (42°N) to the northern Labrador Sea/Davis Strait (65°N), is an area in which metazoan, microbial and under-ice food webs may play differing roles in determining regional productivity. All parts of the region are characterized either by a temperate or polar seasonal cycle of phytoplankton production in which the spring phytoplankton bloom is dominated by diatoms but in which dinoflagellates and smaller taxa become dominant following depletion of nutrients in the upper water column. Seasonal ice cover on the Newfoundland and Labrador Shelves and in the Gulf of St. Lawrence, which sometimes spills onto the Eastern Scotian Shelf, has been a significant feature of those ecosystems (ecoregions) although recent trends indicate that the duration, extent and thickness of sea ice has been declining (Galbraith et al., 2012). There is considerable variation in both phytoplankton and zooplankton community composition across this region. The large latitudinal extent affects the seasonal light and atmospheric cycles. Differences in currents, water masses, hydrological cycles and bathymetric features determine patterns of life history closure among taxa in different parts of the region.

Lower trophic levels can serve as the harbingers of changes in ecosystem productivity in response to environmental and climate change because most functional and taxonomic groups have life cycles that are annual or seasonal in duration. Their production is strongly linked to the physical state of their habitat, their dispersal is strongly affected by changes in circulation, and their physiology is strongly affected by temperature. Variations in the abundance and distribution of lower trophic levels have been closely linked to variations in atmospheric processes that affect ocean state such that time series observations can provide insight into the factors that may regulate regional production potential. How such changes may affect regional productivity should have consequences for exploitation of marine renewable resources (e.g., fish and invertebrate stocks) which in turn would require operational adaptations by Fisheries and Oceans Canada in order to ensure environmental sustainability and conservation and economic well-being.

Our objective is to provide an overview of the key factors that are likely to affect the dynamics of lower trophic levels (phytoplankton and zooplankton) in the Atlantic Large Aquatic Basin (Atlantic LAB) based on a review of existing literature dealing with the potential effects of climate change on these organisms as well as current knowledge of the state and trends in populations or communities as part of the risk assessment process focussed on institutional (Sector) adaptations required to address climate change. To achieve our goal, the review was intended as comprehensive but not exhaustive, owing largely to time constraints and the availability of information that was pertinent to the Atlantic LAB. For example, limited effort has been dedicated to dealing with under-ice communities or with the role of the microbial food web because baseline information about these elements in the region was so limited that any inferences about potential changes associated with climate change would be largely speculative and therefore of little value in a risk assessment process. The review was guided by information, summarized by a group consisting largely of physical oceanographers, which would provide an overview of past trends and future projections of key environmental variables that would affect biotic and abiotic resources, as well as operational activities, in the Atlantic LAB.

3.2 PHYTOPLANKTON

Phytoplankton play a critical role in marine food webs as well as a key role in the biogeochemical cycling of carbon and nutrients. The scale of phytoplankton production is similar to that of plants in terrestrial ecosystems and therefore it provides approximately half of the earth's primary production (Longhurst et al., 1995). Phytoplankton also extract dissolved CO_2 and fix it to organic carbon which can then be exported to the deep ocean where it is stored on a geologic timescale. This biological pump may act as a negative feedback for increasing atmospheric CO_2. As an ectothermic group that is not commercially exploited, they should directly reflect changes in their environment through their abundance and population structure (Hays et al., 2005; Beardall and Stojkovic 2006). Their short life-span also means the response to climate changes can be rapid. Shifts in this community will have important implications for the movement of energy through ecosystems, with bottom-up effects on the productivity of other groups such as larval fish and also on the global carbon cycle.

The distribution and structure of phytoplankton populations are determined by the interplay of environmental factors including temperature, light exposure, and the availability of nutrients (N, P, Fe, and Si) (Behrenfeld et al., 2006). Climate change will result in an overall increase in temperature as well as a host of related changes in the environment that may impact primary productivity. Higher temperatures may impact the physiology of phytoplankton directly, but may also indirectly impact ocean circulation, water column stability, and storminess in turn affecting nutrient and light availability. Increasing levels of atmospheric CO_2 will lead to higher dissolved CO_2 concentrations in seawater that will alter carbonate equilibrium. Changes in carbonate chemistry will lead to acidification and under saturation with respect to the important forms of biogenic carbonate (aragonite and calcite). The direction and magnitude of these impacts on phytoplankton are not always clear. It is possible that some may have opposing effects on phytoplankton production and will vary between regions.

Studies have been attempting to measure global changes in phytoplankton biomass. This effort is complicated by the scales involved; from the microscopic size of the phytoplankton to the large geographic scale of the areas. The effort has been aided by the development of methods that use satellites to detect changes in chlorophyll (Chl) from space (Chavez et al., 2011; Bode et al., 2011). Changes in abundance from year to year are small when compared with the total stock of phytoplankton and therefore can be hard to detect (Behrenfeld et al., 2006), but the sensitivity of these new methods makes this possible. Conflicting results have still been reported. Antoine et al. (2005) measured changes in global chlorophyll using these methods, and found an overall increase of 22% between 1979–1986 and 1998-2002. This was mostly due to an increase in tropical areas, and to a lesser extent, increases at higher latitudes. In the Atlantic Ocean, concentrations increased. Another study examining the period from 1899, found that there has a general decline in phytoplankton biomass of approximately 1% of the global mean per year (Boyce et al., 2010). They found that this long-term decline was strongly linked with increasing sea surface temperatures (SST). However, some methodological concerns have been raised about this study (Mackas 2011; Rykaczewski and Dunne 2011; McQuatters-Gollop et al., 2011). Gregg et al. (2005) found that chlorophyll had increased by 4.1% globally over a six-year period, mostly attributable to increases in coastal areas. Mid-ocean gyres, including the Atlantic, did show some decline. Some work may still be needed to improve these estimates. Taucher and Oschilies (2011) have suggested that chlorophyll may not be a good indicator of climate influence because it may decrease in cells as a physiological response to light.

Regionally, conditions may respond differently to the changing climate. The area of the Northwest Atlantic considered here, from the Labrador Sea to the Scotian

Shelf, presents a unique and complex set of conditions combining Arctic and subtropical environments (Longhurst 2007). Phytoplankton in these areas will encounter different combinations of pressures and different responses may be seen across the region.

As climate change pushes conditions beyond the optimal for individual species, phytoplankton may respond by adapting or shifting from their current distributions. If adaptation is not possible, they die out (Doney et al., 2012). While they have some capacity to move vertically, phytoplankton lack the mobility that would allow them to deliberately shift their range. The sum of these changes for the ecosystem may be a shift in species composition that can impact food webs and nutrient cycling. It may be found that these changes happen rapidly, and tipping points may lead to large shifts in ecosystem community structure (Beaugrand 2009).

Two of the important phytoplankton functional groups are diatoms and dinoflagellates. Diatoms have silica tests and tend to dominate when nutrient levels are high. As a group, they may be responsible for as much as 40% of phytoplankton primary production (Boyd et al., 2010). Dinoflagellates have flagella that give them some mobility and may allow them to more readily compensate for changes in nutrients and light than other species. Another important group is coccolithophores. These are a calcifying group of phytoplankton that occasionally form large blooms. They are small in size (5-20 μm), and may be responsible for a third of marine biogenic carbonate production (Riebesell et al., 2000; Gregg and Casey 2007; Poulton et al., 2007; Iglesias-Rodriguez et al., 2008). In low productivity subtropical areas, coccolithophores may provide over 20% of total carbon fixation (Poulton et al., 2007). Phytoplankton are often grouped according to size. Picophytoplankton have diameters < 2 μm but may account for at least 10% of primary productivity, and may especially dominate oligotrophic areas (Agawin et al., 2000; Morán et al., 2010). Other size-based groups that may be identified include nanophytoplankton (2-20 μm) and microphytoplankton (> 20 μm) (Li et al., 2006a,b).

3.2.1 Carbon Dioxide

Increasing atmospheric CO_2 concentrations will have implications beyond causing global temperatures to increase. The oceans act as a sink for CO_2, causing dissolved CO_2 levels in the upper ocean to increase. This may lead to CO_2 levels up to 3 times the pre-industrial value by the end of the next century (Riebesell et al., 2000). This can have both direct and indirect impacts on marine organisms. Physiological processes may be impacted by higher CO_2 concentrations and seawater chemistry will undergo significant alteration.

3.2.1.1 Direct effects

Increasing dissolved CO_2 in seawater may have a direct impact on photosynthesis, but it may also have an indirect effect on productivity through changes in pH and carbonate equilibrium. CO_2 fertilization is often discussed in reviews of possible climate change effects. Higher dissolved CO_2 may act to promote photosynthesis, but it also leads to higher acidity that may reduce productivity and calcification (Boyd 2011).

During photosynthesis, phytoplankton assimilate carbon from the dissolved inorganic pool, but the uptake mechanism varies among species. This implies that impacts from changing CO_2 will be felt differently. Some species are able to assimilate CO_2 directly while others rely on the other dominant dissolved carbon species (HCO_3^- or CO_3^{2-}) (Riebesell 2004). Many phytoplankton utilize a carbon concentration mechanism (CCM) to overcome under-saturation with respect to dissolved carbon concentrations. Increasing dissolved CO_2 may therefore be beneficial for some, particularly those without a CCM. Even with a CCM, differences in efficiency may lead to different responses to increased CO_2 (Beardall and Stojkovic 2006). Shifting the carbonate equilibrium will also lead to higher concentrations of HCO_3^- while CO_3^{2-} concentrations may be cut by 50% (for a doubling of atmospheric CO_2) (Beardall et al., 2009). Again, the impact of this shift will vary by species depending on the favoured mechanism.

A potential confounding factor is the synergistic relationship that may exist between high CO_2 levels and light. Gao et al. (2012) performed shipboard microcosm experiments in the South China Sea to examine the interaction between high CO_2 concentrations and light. They found that at a P_{CO2} (carbon dioxide partial pressure) of 800-1000 µatm and increased light, productivity was reduced relative to ambient conditions (P_{CO2} = 385 µatm). Their explanation was that, with increased dissolved CO_2, the phytoplankton needed less energy for carbon acquisition and therefore their threshold for light tolerance was lowered, causing them to be stressed. They also found that there was a relative shift in species composition with diatoms decreasing and haptophytes increasing. It is also possible that phytoplankton utilizing a CCM may be energy limited if light levels are low because they require greater energy to use this mechanism (Riebesell 2004).

It seems that for most diatom species, the level of dissolved CO_2 in the present oceans is approximately at saturation for photosynthesis while coccolithophores are well below saturation (Riebesell et al., 2000; Riebesell 2004). Schippers et al. (2004) reported that there might be an increase of up to 40% in production for species presently limited by carbon. A mesocosm experiment in the Equatorial Pacific found diatoms were favoured under high CO_2 concentrations compared with haptophytes with an overall increase in productivity (Tortell et al., 2002).

Other possible responses of phytoplankton to increased CO_2 concentrations include changes in their elemental ratios such as C:N:P. This arises because of changes in their relative rates of uptake (Riebesell 2004; Beardall et al., 2009; Finkel et al., 2010). Fatty acids can also be affected, and phytoplankton may increase production of extracellular molecules such as polysaccharides. These can promote aggregation of cells leading to enhanced export to the deep ocean (Beardall et al., 2009). The nutritional value of phytoplankton can also be negatively impacted by these changes thus affecting the entire food web (Beardall et al., 2009).

3.2.1.2 Acidification

The mean pre-industrial pH of seawater was 8.2. As more CO_2 has entered the oceans, this value has decreased by 0.12, and it is predicted that values will fall 0.3 units by the end of the century under a "business-as-usual" scenario (Riebesell 2004; Freely et al., 2009). Cold waters will be able to absorb more CO_2 and will therefore become acidified more rapidly (Keeling 2010). In this region, projections show that pH is very likely to decrease (likely between 0.1 and 0.2 pH units) over the next 50 years.

Species may be impacted to different extents by increasing acidity. For calcifying organisms, their shells may experience dissolution as seawater becomes undersaturated with respect to $CaCO_3$. Aragonite will be undersaturated before calcite leading to differences among species. It will also become more difficult to form shells as CO_3^{2-} concentrations decrease. Growth rates, reproduction, development, and survival for organisms may also be negatively impacted, but these effects will vary between species and developmental stages (Kroeker et al., 2010).

The impact of acidification on calcification by coccolithophores has been somewhat controversial. These phytoplankton produce carbonate tests called coccoliths and play an important role in primary productivity and the biological pump (Smith et al., 2012). Earlier studies had found that with the addition of acid to cultures of coccolithophores, calcification rates decreased (Riebesell et al., 2000; Riebesell 2004). These results were later challenged by Iglesias-Rodriguez et al. (2008) who found an increase in calcification. The discrepancy, they believed, was due to the different methodologies used to achieve lower pH values in the two studies. Further support for increased calcification rates comes from an observational study by Smith et al. (2012) who found a seasonal shift in the morphotype of coccolithophores in the Bay of Biscay. In winter, a greater proportion of the heavily calcified form was observed to correspond with lower carbonate saturation levels.

More recently, Beaufort et al. (2011) measured the mass of coccoliths in sediment cores through a 40,000-year time series and compared this with contemporaneous seawater carbonate concentrations. They found that the mass of carbonate declined as dissolved CO_2 levels increased, consistent with the findings of Riebesell et al. (2000). They also found that shifts in species composition played an important role in this decline. Less heavily calcified species seemed to be favoured at higher CO_2 concentrations. These results also provide a possible explanation for the findings of Iglesias-Rodriguez et al. (2008) and Smith et al (2012) because the species used in those studies (E. Huxleyi) seems to be the exception, becoming more abundant with increasing CO_2.

Azetsu-Scott et al. (2010) demonstrated that water with low saturation states for calcite and aragonite in the Arctic moves down into the Labrador Sea. At the time of their study, the aragonite saturation horizon was at 2300m in the Labrador Sea. As the Arctic Ocean becomes more acidified, it is likely that this will have a downstream effect on the Northwest Atlantic Region through the Labrador Sea.

Orr et al (2005), while studying the Southern Ocean, have predicted that high-latitude surface oceans will become undersaturated with-respect-to aragonite within 50 years. Undersaturation for calcite will lag aragonite by 50-100 years. Yamamoto-Kawai et al (2009), working in the Canadian Arctic, showed that the problem can be exacerbated by mixing with sea-ice melt water. This led to surface waters that were undersaturated with respect to aragonite. Projections for the Atlantic LAB indicate that it is likely there will be a large reduction in the aragonite saturation depth over northern areas that may approach the surface over the next 50 years.

Generally, higher dissolved CO_2 concentrations may lead to enhanced productivity in some cases, however because this is largely species specific, the information needed to make any projections is very limited. Acidity values will continue to decrease and while this may prove beneficial for some species, in the long term the impact is likely to be negative, especially for calcifying organisms.

3.2.2 Temperature

Increasing temperature is the most widely anticipated consequence of climate change. Globally, sea surface temperatures are expected to rise by 2-3 °C, but there will be strong regional differences (Beardall and Stojkovic 2006). In this region, warming is very likely for all areas and seasons, although the projected magnitudes vary. The Scotian Shelf (SS), Gulf of Maine (GoM), and Gulf of St. Lawrence (GSL) are likely to experience the greatest warming (1.5 to 4 °C) within the next 50 years, while the northern areas of the Newfoundland and Labrador Shelves are likely to experience warming of 0-2 °C with slight seasonal differences. On a decadal scale, there is a moderately likely chance of an increase of < 1 °C, but natural variability could mask the effects of climate change to some extent.

3.2.2.1 Direct effects

Temperature may have important direct physiological impacts on phytoplankton (Behrenfeld et al., 2006). Individually, it may impact metabolism, feeding, respiration, growth and reproduction. At the species and ecosystem levels, it may impact life history, survival, distribution, species composition, and size (Beaugrand 2009). Gaining information on how these changes relate to temperature will be important for understanding the future impacts of climate change.

Generally, as temperature increases, phytoplankton metabolic rates are expected to rise along with rates of photosynthesis and growth (Doney et al., 2012). A comparison between specific metabolic rates and water temperature was carried out by Regaudie-de-Gioux and Duarte (2012) using data from open ocean reports between 1996 and 2010. They demonstrated that there was a direct correlation, in agreement with standard metabolic theory. In the north Atlantic, Li et al. (2006a) found that temperature could explain 75% of the variance in phytoplankton cell abundance on the Scotian Shelf and Labrador Sea.

With increasing temperature, metabolism will continue to increase until an optimal growth value, specific to each species, is reached (Beardall et al., 2009; Bode et al., 2011). Although phytoplankton will have a set of environmental conditions optimal for their growth and survival, they can exist within some range of conditions (Beardall et al., 2009). Species with a narrow environmental niche may be more likely to be impacted by even the mildest predictions for climate change while larger niches allow adaptation (Beardall et al., 2009). Once at the edges of their range, species will have to adapt to the new conditions, or if possible, shift their distributions to optimise their environment (Ji et al., 2010). Phytoplankton have a limited ability to respond to changes in temperature in terms of movement, but turnover times for populations are rapid. Since each species will respond differently, this can lead to changes in species composition within a region.

The direct impact of temperature is often ignored in studies modeling primary production that tend to focus on factors such as nutrient concentrations and light. Taucher and Oschlies (2011) carried out a modeling study that showed that the direct impact of temperature plays a key role in determining the direction of changes in productivity. Using a model that did not include temperature sensitivity, they found that photosynthesis decreased, but the opposite trend was found when temperature sensitivity was included. They also found that increased photosynthesis was supported by enhanced microbial loop activity that acts to recycle nutrients within the upper ocean.

It is not really clear which changes may be a direct consequence of temperature or some combination of indirect factors. As discussed above, Boyce et al. (2010) have linked a decline in phytoplankton over the last century to increasing SST, but the study has come under scrutiny. The opposite correlation has been found in the northeast Atlantic where phytoplankton abundance has been increasing with temperature (Beaugrand 2009; Reid et al., 1998). Edwards et al. (2001) found that an increase in biomass in the North Sea over a 10-year period was directly related to an increase in SST, but no clear correlation has been found with temperature in the Northwest Atlantic (Reid and Valdés 2011). Any increase in productivity with temperature may also be complicated by the need for increased nutrient uptake or the local light regime. It is possible that these factors may have opposite effects on productivity and act as a balance to climate change (Behrenfeld 2011; Reid and Valdés 2011).

3.2.2.2 Stratification

At least as important as the direct impacts, indirect effects of temperature on stratification and stability of the water column can exert significant control on phytoplankton populations. Circulation and stability are influenced by temperature gradients with depth as well as between the land and the ocean (Falkowski and Oliver 2007; Reid and Valdés 2011). Stratification of the water column results when a layer of warm, less dense water is formed over cooler, denser water and mixing is inhibited. The upper ocean is heated by the sun and therefore the degree of stratification varies by latitude and season. Other factors that will influence stratification include precipitation, evaporation, sea-ice, and freshwater runoff from land. In warm tropical areas, a stronger gradient can lead to semi-permanent stratification while at higher latitudes, where the gradient is reduced, intense mixing can occur. In temperate latitudes, as in the Northwest Atlantic, stratification occurs with spring/summer surface heating and breaks down in fall when cooling allows mixing to occur. In coastal areas, mixing can be encouraged by alongshore winds which can push surface waters offshore allowing upwelling of water from depth.

Climate change will influence many of the parameters that determine the degree of stratification and upwelling. Increased warming of the upper ocean will enhance the thermal gradient and therefore increase the degree of stratification. Changes in evaporation/precipitation patterns, enhanced sea-ice melt, and increased freshwater runoff will also generally act to enhance stratification. Atmospheric warming will tend to increase winds and storminess that can also affect circulation and disrupt water column stability and may tend to encourage upwelling (Beardall et al., 2009).

Long-term forecasts for the Atlantic LAB project that near-surface stratification is very likely to increase for all areas over the next 50 years, and will very likely start earlier and end later. The mixed layer depth (MLD) is also very likely to decrease, although with a greater magnitude, in the north of the LAB. Stratification is moderately likely to experience a small increase and a decrease in the MLD over the next decade.

The productivity of phytoplankton depends to different degrees on the concentrations of nutrients including nitrogen, phosphorous, iron, and silicon (Boyd et al., 2010). The intensity of ocean mixing is seen as a key factor influencing phytoplankton productivity because it helps determine exposure to nutrients and light. Nutrient-rich waters from depth become distributed throughout the water column as mixing occurs. With stratification, this transport of nutrients is blocked and they become depleted, supressing phytoplankton production.

Enhanced stratification is expected to lead to a global expansion of the extent of oligotrophic (low nutrient) areas (Sarmiento et al., 2004). Polovina et al. (2008) found that areas with < 0.0070 mg Chl/m^3 increased in the Atlantic and Pacific oceans by 15% between 1998 and 2006. The North Atlantic increased most rapidly at 4.3%/year. In areas that are presently oligotrophic, increased stratification may further inhibit refreshing of nutrients causing productivity to decline (Bode et al., 2011). Regionally, enhanced upwelling may counter this decrease to some extent (Bakun, 1990).

Bopp et al. (2001) found that at 2xCO_2 concentrations, increased stratification resulted in reduced nutrients and with increased light. Overall, a longer growing season would cause productivity to shift towards the higher latitudes. Export was reduced by 6% although there were large regional differences (both positive and negative). Under a 4xCO_2 scenario, nutrients would become depleted in surface waters and primary production would decrease by 15%, largely driven by decreases in oligotrophic areas (Bopp et al., 2005). Again, some increase in productivity would occur at higher latitudes based on the longer grower season.

Sarmiento et al. (2004) also carried out modeling of global ocean responses to warming with similar findings. Increased vertical stratification would limit productivity in most areas but cause longer growing seasons at high latitudes. Overall, they estimated that there would be an increase in global primary productivity between 0.7% to 8.1% with considerable variability among different regions.

Using satellite measurements of ocean chlorophyll concentrations, Behrenfeld et al. (2006) examined the effect of climate on productivity levels by comparing them with an index of climate (MEI) over the period of a decade. They found that changes in chlorophyll, and therefore productivity, co-varied with climate, and believed reductions in productivity at lower latitudes were linked to reduced nutrient levels caused by the inhibition of mixing brought about by surface warming. At higher latitudes their model showed that productivity should see the opposite effect because stratification in these areas would allow phytoplankton to have increased light exposure thereby increasing productivity (Behrenfeld et al., 2006; Doney 2006).

Nutrient concentrations within the region have varied both spatially and temporally over the past decades with no consistent trends (Pepin et al., 2013). Since 1960, nutrient levels within the eastern Labrador Sea and central Scotian Shelf have showed a significant decline, while there has been an increase in the Gulf of St. Lawrence (Pepin et al., 2013). The western Labrador Sea experienced declines in nitrate and phosphate while silica increased. Trends in the Gulf of Maine and the Bay of Fundy were in the opposite direction. Within the LAB, it is likely that in the next 50 years, there will be a widespread reduction in the supply of nutrients to the upper ocean because of increased stratification.

In the late 1980s there was an increased flow of low-salinity Arctic water to the North Atlantic resulting in a freshening of the water between the Labrador Sea and the mid-Atlantic Bight (Greene and Pershing 2007; Ji et al., 2007a and b). It is believed that this was the result of increased freshwater runoff off and sea-ice melt in the Arctic. This decrease in salinity led to increased stratification and phytoplankton productivity in autumn.

Since the early 1990s, reduced salinity has caused an increasing trend in stratification at Station 27, which is located on the Newfoundland Shelf (Craig et al., 2001; Craig and Colbourne 2002). Lower salinity along with warmer temperatures acted equally to increase stratification in the early 2000s. Increased phytoplankton abundances observed on the Newfoundland and Scotian Shelves between 1958 and 2006 are believed to be linked to this increased stratification (Head and Pepin 2010a). On the Scotian Shelf, Johns et al. (2003) also found that phytoplankton colour index (PCI) increased over a 10 year period which was related to increased stratification. The influence of sea-ice melt on freshening may continue as sea-ice continues to decline although it would be expected to have reduced importance over time.

Exposure to light is also important for phytoplankton productivity. Baseline irradiance for any location is determined by latitude and season, but mixing, sea-ice cover and atmospheric conditions can also determine exposure. The impact will likely be felt more at higher latitudes where annual light levels vary the most (Behrenfeld et al., 2006; Harrison and Li 2008). With increasing temperatures, higher latitudes will experience a decrease in sea-ice that will result in a longer growing season for phytoplankton. In addition, the increased stratification will keep phytoplankton from being mixed to deep water where they would be light limited (Harrison and Li 2008). As a result, overall productivity in these high latitude regions may actually increase (Behrenfeld et al., 2006; Reid and Valdés 2011).

Work by Arrigo et al. (2008) using satellite data from the Arctic measured an increase in productivity of 27.5 Tg C/yr between 2003 and 2005 which increased to 35 Tg C/yr between 2006 and 2007. Sea-ice coverage had decreased by 23% below the previous minimum and the duration of the growing season was lengthened by 70%. In addition to increased light levels, loss of sea-ice can contribute to higher fall and winter temperatures. Contrary to previous expectations, Arrigo et al (2012) found that extensive blooms can occur beneath sea-ice, which may indicate that primary productivity based on open ocean values may have underestimated productivity for these areas. Also, while productivity may tend to shift poleward as a result of changes in temperature and stratification, any benefit may be mitigated by changes in light exposure. Harrison and Li (2008) reported that observations from the Labrador Sea Monitoring Program indicate that, even during summer, light is the principal limiting factor for phytoplankton production and growth in this area.

The amount of sea-ice in the Atlantic LAB is very likely to decrease over both the short and long-term. The greatest decrease will be in southern areas including the Scotian Shelf and Gulf of Maine, where it may disappear completely. The Gulf of St. Lawrence and Newfoundland Labrador Shelves/Slopes will also experience large decreases.

While temperature can have both negative and positive influences on net primary productivity, the overall impact on phytoplankton populations will be more complex. Research has focused on how shifts in temperature and nutrients can lead to changes in community structure including species composition and average size. Changes may occur in phytoplankton phenology affecting not only particular species but also the interactions between species. Again, this has important implications for the rates of carbon cycling and for higher levels of the food web.

Irwin et al (2012) examined continuous plankton recorder (CPR) data for the North Atlantic along with climate data, to determine the preferred niches for phytoplankton species. These were expressed in terms of the mean and range for environmental variables including SST, salinity, nutrients, mixed layer depth, and irradiance. They found that the two main groups, diatoms and dinoflagellates, could be clearly distinguished in terms of their preferences with only some overlap. Diatoms tended to prefer cooler, fresher water with higher nutrient levels, while dinoflagellates preferred warmer, more saline waters with lower nutrient levels. Irwin et al (2012) also attempted to characterize species as generalists or specialists by comparing the range of their preferred conditions to the overall variability of the North Atlantic environment. They found that some dinoflagellates were specialists for high temperatures, high salinities, or low nutrient concentrations while the irradiance specialists were diatoms. As this study was based on observational data, it may be more representative than experimental data when used for modeling climate change impacts.

Under conditions of $4xCO_2$, diatom abundance could be reduced by as much as 10% globally and 60% within the North Atlantic with smaller phytoplankton being favoured according to Bopp et al (2005). A decline in diatom abundance is likely linked to decreasing NO_3 and Si concentrations. These ecosystem changes also result in a reduction of the biological pump with carbon export decreasing up to 25% while recycling via the microbial loop would increase. It would seem that increased stratification will lead to the depletion of nutrients, but this picture is complicated by increased recycling through the microbial loop. Organic matter from phytoplankton is broken down before it can sink through to the deep ocean, and is used to support further productivity. The balance between recycled carbon and that which is removed to the deep ocean will be another factor to consider when looking at the strength of the negative feedback provided by photoplankton productivity.

Research seems to be showing that temperature and nutrient conditions can influence not only the presence of particular species, but also the average size. Higher temperatures seem to favour smaller phytoplankton species at greater numerical abundances, leading to changes in the overall community (Li et al., 2009; Daufresne et al., 2009; Morán et al., 2010). Atkinson et al (2003) found a linear relationship between temperature and cell size for ectotherms which decreased by approximately 2.5%/°C. This relationship was consistent across habitats and taxa. A shift to smaller cell size could have important consequences for ecosystem energy flow. Warming leads to more recycling and less export of carbon to the deep ocean as smaller phytoplankton will settle more slowly and are more likely to be degraded in the upper water column (Beaugrand 2009; Bode et al., 2011).

In the North Atlantic, Morán et al (2010) examined the relationship of increasing picophytoplankton biomass with temperature. They found that temperature could explain 73% of the variance in the relative contribution of picophytoplankton to total biomass. This effect was independent of nutrient status. They predict that with higher ocean temperatures, there will be a shift to picophytoplankton with an impact on the overall ecosystem. These shifts may arise because smaller phytoplankton have an inherent advantage when competing with larger phytoplankton in a low nutrient environment (Falkowski and Oliver 2007; Agawin et al 2000). The ability of phytoplankton to take up nutrients is dependent on how well they overcome the boundary layer around their cells. Mobile phytoplankton such as dinoflagellates may move to areas with higher nutrients, but others will be dependent on the degree of active mixing to bring nutrients to them. This means that nutrient concentrations and turbulence will influence productivity (Falkowski and Oliver 2007). Lower nutrient levels and calm conditions will tend to favour small individuals and species. Their small size means that they have a larger surface area to volume ratio, and therefore their ability to absorb nutrients under these conditions is greater. Larger phytoplankton such as diatoms may, however, be favoured in areas which experience pulses of nutrients, as can occur in areas with significant upwelling. Examining the fossil record, Falkowski and Oliver (2007) found that even though the number of diatom species had increased over 34 Ma, their size had actually decreased. They believed that this demonstrates the overriding impact of climate and ocean mixing on phytoplankton community composition. Also, the selection of small-sized organisms with warming may not be limited to phytoplankton, and may be a common response among species to climate change (Daufresne et al., 2009).

Picophytoplankton seem to dominate in warm, oligotrophic waters, but in reviewing the literature, Agawin et al (2000) found that it is difficult to unravel the effects of temperature and nutrients. They therefore carried out mesocosm experiments in the Mediterranean to test how changes in nutrients impacted abundance during summer. They confirmed that the proportion of picophytoplankton decreased with increasing nutrient levels, and it was linked to their ability to compete under different nutrient states. In warm, oligotrophic areas they are more efficient and have higher growth rates than larger phytoplankton. As nutrient levels increase however, the larger phytoplankton outcompete small phytoplankton because of their higher growth potential. They found that the cut-off for picoplankton dominance seemed to be when $NO_3 + NO_2 > 1$microM. In cold (< 3 °C) waters, above this concentration, picophytoplankton were < 10% of the total phytoplankton biomass while in warm (> 26 °C) waters with lower concentrations, they could be > 50% of the biomass. The advantage of a large surface area to volume ratio also gives picophytoplankton an advantage with light absorption efficiency (Agawin et al., 2000).

Working in the Canadian High Arctic, Ardyna et al (2011) studied the changes in community structure between areas with different levels of productivity. Oligotrophic areas were dominated by flagellates and picophytoplankton, but areas with higher nutrient concentrations had high abundances of centric diatoms. These differences in productivity were driven by stratification. Also working in the Arctic, Li et al (2009) found that freshening of the surface has led to increased stratification and decreased nutrient levels. In turn, the abundance of picoplankton increased and larger nanoplankton (2 to 20 mm) abundance decreased. Li et al (2009) pointed out that carbon export from a system based on picoplankton would likely be lower.

In the Labrador Sea and Scotian Shelf, Li et al (2006a) studied phytoplankton communities and found that numerical cell abundance fluctuated with temperature, reaching a maximum in autumn. Li and Harrison (2008) found that nanophytoplankton and picophytoplankton biomass fluctuations in Bedford Basin were directly related to temperature in contrast with diatom biomass which was significantly related to stratification. Change may therefore involve a combination of factors. Johns et al (2003) also observed a shift in species composition on the Scotian Shelf to dinoflagellates along with increasing PCI.

Generally, for the Newfoundland and Labrador Shelves, and eastern and western Scotian Shelf, Head and Sameoto (2007) found that trends in plankton abundance were largely comparable among areas. During the 1990s and continuing until 2003, diatoms, dinoflagellates, and the PCI all increased along with the increased stratification from freshening of the water column seen at that time. Harrison and Li (2008) have shown that in the Labrador Sea, NO_3 and SiO_2 are potentially limiting in the summer. Some spatial variability is evident as it shifts from being NO_3 limited on the shelf to SiO_2 limited in the basin. Work by the Labrador Sea Monitoring Program has also found that biomass is decreasing despite the decrease in the MLD with warming. Increased stratification along with changes in nutrient ratios (N:Si increase) are linked to changes in the community structure as diatoms are becoming less abundant while smaller phytoplankton are increasing.

Coccolithophores may also change their distribution based on competition for nutrients and light (Gregg and Casey 2007). Like dinoflagellates, they have a greater ability to live at low concentrations of nutrients and light, and therefore they outcompete diatoms and chlorophytes but not cyanobacteria (Gregg and Casey 2007). Under higher nutrient conditions however, they lose their advantage because of their higher sinking rates.

Changing conditions or shifts in circulation patterns and water masses with climate change may also lead to the introduction of new species. Reid et al (2007) found a Pacific diatom species, *Neodenticula seminae*, during May 1999, in the Labrador Sea which they believe was linked to decreasing ice cover in the Arctic. *N. seminae* were also observed in the Gulf of St. Lawrence following the intrusion of cold surface waters from the Labrador Shelf in 2001 (Starr et al., 2002). During the 1990s, CPR data showed that the dinoflagellate *Ceratium arcticum* had become much more abundant in the northwest Atlantic (Johns et al 2001; Johns et al., 2003). On the Newfoundland Grand Banks, it became a dominant winter (December to February) species where it had not been before (Johns et al., 2003). This species is generally only found in the Arctic, in waters < 15 °C. Johns et al (2003) felt that this shift was likely linked to changes in stratification due to the influx of cold, fresh water from the Arctic (Craig and Colbourne 2002). The largest contribution of *C. arcticum* was in 1996 when particularly high levels of fresh water were observed.

It seems that it is likely that the overall Atlantic LAB will see shifts towards smaller phytoplankton, decreased productivity, and decreased export related to increased stratification and decreased nutrients. There may be some benefit in northern areas where increased light availability due to decreased sea-ice may lead to a longer growing season. Knowledge of the factors involved in these shifts is still very limited.

3.2.3 Phenology

Changes in the phenology or the annual life cycle of a species may be one of the first responses to be expected due to climate change (Beaugrand 2009). By changing its life cycle, it may be possible for a species to maintain its present range (Beaugrand 2009). Phytoplankton have evolved the timing of reproduction, growth, and various life stages to match the most advantageous environmental conditions and to manage interactions with other species (Ji et al., 2010). Some organisms may be limited in their ability to adjust due to other factors such as the local light regime or the activities of other organisms. For example, diatoms may be more limited in their ability to shift their annual cycle because of their dependence on light (Eilertsen et al., 1995; Beaugrand 2009; Edwards and Richardson 2004). In contrast, the mobility of dinoflagellates may allow them to compensate for changes in light more easily than free-floating plankton species (Head and Pepin 2010a).

The northwest Atlantic is a hydrographically complex and biologically active area where all the factors that potentially influence stratification, and therefore phytoplankton, are found. The seasonal cycle of primary production typical on the shelves of this area demonstrates the linkage between stratification, nutrients, and phytoplankton (Johns et al 2003; Longhurst, 2007; Harrison and Li 2008; Ji et al 2008). In spring, the onset of stratification and increased light brings about a large phytoplankton bloom dominated by diatoms (Johns et al., 2003). As nutrients become depleted, and herbivorous grazing exerts a top-down control on the phytoplankton population, the bloom period ends (Martinez et al 2011). In autumn a smaller but longer bloom occurs, which is dominated by dinoflagellates (Johns et al 2003; Ji et al., 2007a). This bloom is likely stimulated by increased vertical mixing as cooling occurs (Ji et al., 2010).

In the North Sea, CPR data from 1958 to 2002 showed that spring and autumn peaks of diatom abundance remained relatively stable, although with some variability between taxon. Most dinoflagellates, however, shifted to an earlier peak by up to 23 days (Edwards and Richardson 2004). Diatom development may be more dependent on photoperiod, meaning that their peak bloom remains more constant. Dinoflagellates were believed to be responding physiologically and also enhanced stratification. The data also indicated that species that peaked during low turbulence conditions were likely to advance their peak timing. When species-specific changes like this occur, it may lead to a decoupling between predators prey that may influence the top-down control of predator grazing on phytoplankton population size.

Spatial variability in the timing of blooms on the SS has been found to be influenced by salinity changes (Sameoto 2001; Ji et al., 2007a and b; Ji et al 2008). Cool, fresh water from the Gulf of St. Lawrence (GSL) tends to influence the eastern side of the shelf while warmer, higher salinity water from the slope influences the western shelf (Sameoto 2001). Ji et al. (2007a and b) examined how changes in the water mass characteristics impacted the progression of the spring bloom across the SS and Gulf of Maine (GoM) region. The bloom in this region starts upstream on the SS and progresses westward to the GoM. This timing is linked to freshening of the water column. Enhancement of this salinity gradient, caused by increased input of fresh water from the Arctic, caused a shift to earlier blooms upstream. Ji et al. (2008) used modeling of this system to confirm their observational results. Freshening impacted stratification, causing enhanced stratification that stimulated the earlier bloom, but moving westward, the influence was diminished.

The fall bloom in the SS–GoM region seems to progress in the opposite direction (from the GoM to the SS), and the timing is related to both salinity and SST (Song et al., 2010). Both have an effect on water column stability, but in opposite directions. Modeling by Song et al. (2010) also showed that higher nutrient concentrations could increase bloom magnitude but only had a weak effect on timing. Annual productivity in the area reflects a balance of nutrient availability and light limitation, again responding in opposite directions to stratification (Song et al., 2011).

In the western Gulf of St. Lawrence, a bloom occurs in spring as soon as the ice cover breaks up allowing light penetration (Longhurst 2007). This may be less of a factor as less sea-ice forms in the future.

Spring bloom on the Newfoundland Shelf seems to coincide with the onset of stratification in the water column as seen at Station 27 (Craig et al., 2001). Examination of CPR data from 1961 to 2003 has shown that generally, the timing of the spring and autumn phytoplankton blooms on the Newfoundland Grand Banks has been very consistent although there is interannual variability (Maillet and Pepin 2005; Head and Pepin 2010c). It is possible that, in this area, light is playing a larger role in regulating this timing than nutrient concentrations. This contrasts with work in the North Sea where earlier phytoplankton blooms have been linked to warmer temperatures (Maillet and Pepin 2005). Recently in 2010, the spring bloom was earlier, longer, and more intense than usual (Pepin, unpublished data). These enhanced blooms were found from Scotian Shelf and the Gulf of St. Lawrence to the Newfoundland Shelf and Grand Banks (Maillet et al., 2011). It was speculated that this might have been related to the mild winter in 2010 and low sea-ice conditions, leading to warmer SST (Pepin, unpublished data). Blooms in the northern areas, including the Labrador Sea and Labrador Shelf, were lower than normal.

Overall, it is likely that the region will see some shift in the timing of seasonal phytoplankton blooms, but the exact nature of these changes are difficult to predict with the present level of knowledge and are complicated by interactions between the various physiological effects. Reduced sea-ice cover in some areas will also have an impact, likely leading to earlier blooms and a lengthened growing season in the more northerly areas.

3.2.4 Harmful Algal Blooms

Harmful algal blooms (HABs), often referred to as ‘red tides’, are another aspect of phytoplankton ecology that needs to be considered in the light of climate change. Some phytoplankton species can produce large blooms that can be hazardous to other organisms. These HAB species may produce toxins that can injure or kill marine organisms, and those that feed on them, including humans. They may also be nontoxic but produce exudates such as reactive oxygen species, polyunsaturated fatty acids (PUFAs), and mucilage that can cause harm; in other cases damage may be caused by the large biomass created by the blooms causing oxygen deprivation and shading (Mudie et al., 2002; Hallengraeff 2010; Anderson et al 2012). Mobile organisms may be able to move away from these blooms, but aquaculture facilities may be more vulnerable to increases in HAB occurrence. While there may be direct impacts on individual organisms or species, so called ecosystem disruptive algal blooms (EDABs) may have a more general negative impact (Hallengraeff 2010).

Generally these blooms are monospecific, but many varieties of phytoplankton can potentially cause HABs (Hallengraeff 2010). One of the more common groups seems to be dinoflagellates, although diatoms, coccolithophores, haptophytes, raphidophytes and cyanobacteria are also observed (Mudie et al., 2002; Hallengraeff 2010). There is general agreement that blooms have become more common, widespread and intense globally in the last thirty years, although this is not true in all regions (e.g., Edwards et al., 2006; Martin et al., 2009). In part, the apparent increase may be due to improved awareness and detection (Edwards et al., 2006; Halengraeff 2010; Anderson et al., 2012). Comparable increases on the Pacific and Atlantic coasts of North America seem to indicate that global scale processes such as climate change and international shipping are influential factors (Mudie et al., 2002).

It is hard to generalize about conditions that will favour HAB development because of the wide variety of species involved and habitats in which they occur (Anderson et al., 2012). Of course they are influenced by the same factors that affect the productivity of phytoplankton as a whole including temperature, salinity, stratification, light, and nutrients (Anderson et al., 2012). The occurrence of blooms is also influenced by circulation and transport processes. Some blooms may not develop in situ but may be carried in from other areas (Martin et al., 2009; Anderson et al., 2012).

Eutrophication has often been thought to be a large driver for HAB development. This relationship has proved not as simple as earlier believed and may be hard to extract from the influence of other variables (Edwards et al., 2006). It appears that it is not simply the concentration of nutrients that is important to stimulate HABs (Anderson et al., 2012). There is also some indication that HAB species may acquire a competitive advantage over other phytoplankton from their ability to use organic compounds to obtain nutrients, and some have been found to be mixotrophic (Hallengraeff 2010; Anderson et al., 2012).

The distribution and survival of HAB species can be influenced by a number of processes. Some species may persist at low levels in the environment for months while other species have a benthic resting cyst stage in their life cycle (Hallengraeff 2010; Anderson et al., 2012). These cysts may remain in the sediment for long periods, allowing them to survive through non-favourable conditions and also aid in transporting them to other areas. Increased storminess caused by climate change may impact the frequency of these blooms by disturbing resting cysts from the sediment. It is also possible that dredging of sediment may stimulate increased blooms (Mudie et al., 2002).

An example of a HAB species that has caused poisoning in Atlantic Canada is *Nitzchia pungens*, a pennate diatom that produces the toxin domoic acid. This toxin causes a neurological condition called amnesic shellfish poisoning (ASP). The first known outbreak causing human poisoning was in cultured blue mussels (*Mytilus edulis*) from PEI in 1987 (Bates 1989, Anderson et al., 2012). The dinoflagellate *Alexandrium fundyense* also occurs in Atlantic Canada and has been responsible for outbreaks of paralytic shellfish poisoning (PSP) (Martin et al 2005). It has been observed in the Bay of Fundy along with *P. nitzschia*, and *M. rubrum*. PSP has also been observed in the Estuary and the Gulf of St. Lawrence since the 1940s. These outbreaks have been correlated with blooms of the dinoflagellate *Alexandrium tamarense* (Blasco et al., 2003).

By studying the palynological record for red-tide forming species in sediments from the Canadian Pacific and Atlantic coasts, Mudie et al (2002) found that warming was most likely to be causing the overall increase in HAB occurrence in these waters. They also observed that past blooms tended not to overlap in time, but this had become more common in recent times indicating disequilibrium in their ecology. This is in agreement with work done by Martin et al (2009) in the Bay of Fundy. They found that abundance was more likely linked with climate and weather rather than nutrient concentrations. In general, understanding how HABs will respond to climate change will involve similar studies as for phytoplankton in general.

In keeping with the observed trend, it is likely that HAB occurrences will continue to be more frequent than in the past. The exact reasons for this increase are not at present fully understood. Aquaculture facilities seem particularly vulnerable to these outbreaks, and therefore it will be important to continue studying this area.

3.3 ZOOPLANKTON

In contrast to phytoplankton, which are influenced by all variables that affect the vertical structure of the water column, the impact of climate change on zooplankton will principally occur as a result of factors that influence their physiology, phenology and distribution. Taken together, the overall effect may alter regional productivity but given the diversity of environments found in the Atlantic basin, local ecosystem characteristics will have to be considered in order to assess the overall vulnerability of the region to climate change.

3.3.1 Temperature Effects

Climate change projections for the region indicate potential increases in SST over the next 50 years from less than 1 °C in some parts of the region to more than 4 °C in more southerly areas, and such increases are likely to be echoed in some way throughout other parts of the water column based on past observations (Han et al. 2013). Changes in the thermal regime in the basin will have direct and immediate impacts on the physiological processes that govern the population dynamics of zooplankton (Richardson, 2008). Basal and active metabolic rates are likely to increase in warmer environments that will translate into faster development times as long as sufficient food resources are available (Richardson, 2008). Most copepods are omnivorous, capable of exploiting blooms of phytoplankton but able to graze on protists and small zooplankton when diatoms and dinoflagellates are scarce, so despite potential changes in primary production associated with climate change, there is limited evidence at this time that development should be severely impeded as a result of climate change (Richardson, 2008).

Faster growth rates, and potentially egg production, would not necessarily imply greater productivity in itself because, like most metabolic processes, mortality rates have also been shown to be highly temperature dependent (Plourde et al., 2009). Plourde et al. (2009) argued that subtle differences in the response of development and mortality rates to temperature could have resulted in differences in the productivity of *Calanus finmarchicus* between the Gulf of St. Lawrence, Scotian and Newfoundland Shelves that were related to the average thermal regime in which the species is found. This could also be considered important for other species, but the availability of information concerning temperature sensitivity of vital rates across a broad range of taxa is limited. In fact, most estimates of the Q_{10}, the change in vital rates incurred as a result of a 10 °C increase in temperature, have been shown to be normally distributed close to a value of ~2 (Hirst and Bunker, 2003, Richardson, 2008). This suggests that estimates for a single study, process or species may well be within the underlying range of estimation error which may be the result of experimental or analytical uncertainties. Consequently, the net effect of temperature increases on the productivity of individual species through physiological processes is uncertain because the changes to processes that affect both growth/reproduction and catabolism/mortality may balance each other. However, heightened development rates and increased rates of mortality have the potential to affect productivity by altering population phenology and life history characteristics.

3.3.2 Ecophysiology of *Calanus* and Likely Response to Climate Change

Calanus finmarchicus is a dominant species throughout the North Atlantic where it represents a significant proportion of the total mesozooplankton biomass. On a broad geographic scale, the abundance of this species demonstrates a strong inverse relationship with temperature, indicative of a polar and subpolar distribution (Reygondeau and Beaugrand, 2011). In the Northeast Atlantic, *C. finmarchicus* has demonstrated a significant shift in its spatial distribution as a result of the progressive warming of surface waters. This shift has yet to be apparent in the western Atlantic, although there have been significant changes in abundance associated with changes in temperature at the southern extreme of its range (Pershing et al., 2010). However, according to Reygondeau and Beaugrand (2011), *C. finmarchicus* has remained prevalent within its ecological (or at least physical) niche and has not demonstrated any significant shift in habitat despite that habitat being displaced in some parts of its past range. These findings indicate that the physical habitat can serve, at least partly, as a tool for forecasting changes in the distribution, and possibly abundance, of this keystone species.

Based on oceanographic model projections of changes in the thermal regime in the North Atlantic over the next 50 years, Reygondeau and Beaugrand (2011) forecasted a likely reduction in suitable habitats for *C. finmarchicus* in the western Atlantic ranging from the Scotian Shelf to Georges Bank as a result of increases in temperature. The projections did not include possible changes in the Gulf of St. Lawrence, but given the information provided by the Trends and Projections group, increases in temperature similar to those projected for the Scotian Shelf appear likely, so we can expect some significant changes in habitat availability for *C. finmarchicus* in that part of the Atlantic LAB as well. Reygondeau and Beaugrand (2011) did not discuss, however, the uncertainty in oceanographic model projections in the western Atlantic associated with inaccuracies in the position of the Gulf Stream or the high degree of variability associated with forecasts for conditions in the southern Labrador Sea. Both of these sources of uncertainty can have significant implications for any inferences about potential changes in productivity of *C. finmarchicus* because the Gulf Stream represents an extreme thermal boundary for this species, and the magnitude of the changes that could occur in the Labrador Sea could move the species toward the upper end of its thermal habitat.

Changes in regional primary productivity are also likely to have an influence on the ecophysiology of *C. finmarchicus*. Helaouet et al. (2011) predicted moderate reductions in egg production in the subpolar gyre as a result of changes in productivity based on a generalized relationship between egg production and temperature. Their analysis did not include the strong non-linearity in egg production noted by Campbell and Head (2000) at low chlorophyll concentrations. Because low chlorophyll concentrations predominate following the spring phytoplankton bloom throughout much of the Atlantic LAB in which *C. finmarchicus* is abundant, the potential reduction in secondary production by this species may be greater than forecast by Helaouet et al. (2011), but it is equally important not to discount the capacity of this species for omnivory. Furthermore, Helaouet et al.'s (2011) projections are based on a similar categorization of the available habitat as Reygondeau and Beaugrand (2011), making inferences about productivity equally subject to the uncertainties in ocean conditions throughout the Atlantic LAB as those concerning the distribution of *C. finmarchicus*.

3.3.3 Phenology

Seasonal variations in temperature, light, prey availability and energy reserves have been considered as potentially significant regulators of zooplankton phenology and productivity. Although the ultimate driver of the seasonal life cycle of most copepods remains uncertain, there is growing evidence that variations in temperature are strongly linked to variations in phenology of mesozooplankton (Mackas et al., 2012). In an assessment based on population time series from most of the world's Oceans, Mackas et al. (2012) concluded that warmer ocean temperatures resulted in earlier onset of population increases or succession for species that normally increase in abundance early in the year. They also found that taxa that peak in abundance later in the year had a delayed peak when ocean temperature was warmer. The phenological response to changing ocean temperature was not uniform within species or between similar communities or oceans. Edwards and Richardson (2004) found that changes in the seasonal cycle of major zooplankton species in the Northeast Atlantic were strongly correlated with the strong and persistent long-term trend in surface temperate in the region. In contrast, Maillet and Pepin (2005) failed to identify a consistent shift in the seasonal cycles or an association with temperature in a similar group of taxa from the Northwest Atlantic, where variations in surface temperatures have not shown a long-term trend but instead have been closely associated with fluctuations in atmosphere processes (e.g., North Atlantic Oscillation, Arctic Oscillation).

The differences in the environmental regimes (i.e., long term trends versus decadal oscillations) may provide a clue about the different responses by zooplankton in the eastern and western Atlantic. Faced with prolonged and persistent changes in the environment, selective forces may begin to alter the life history cycle directionally to maximize productivity or fitness, whereas a variable environment may maintain a diversity of life history adaptations among individuals in a species which in turn results in a lack of association with a single environmental indicator. What is uncertain is the length of time required for persistent selection to result in significant changes in life history. Furthermore, we must question the degree to which changes observed in the eastern Atlantic represent genetic versus phenotypic adaptations to environmental state. For example, *Calanus finmarchicus* and *Pseudocalanus* spp. populations collected from the long term monitoring site Station 27 (S27; 47.55°N 52.59°W) between 1999–2011 have demonstrated a shift in life history strategies from one to two generations per year (Pepin, unpublished). The majority of the spring cohort enters diapause in the autumn, as found in most populations of these species, but Pepin has noted a significant increase in the proportion of stage 5 copepodites that moult into adults to start a second generation, which appear as early stage copepodites in the following year. The shift can be attributed simply to changes in development times caused by a minor shift in the seasonal temperature cycle in which summers have cooled and winters have warmed by approximately 1-1.5 °C, which coupled with earlier spring phytoplankton bloom and a lengthened fall bloom, represents a phenotypic adjustment to local conditions. Both species have demonstrated a gradual increase in abundance during the last decade throughout much of the region (Pepin et al., 2011a). In contrast, *Calanus finmarchicus* sampled at Halifax 2 (HL2; 44.27°N 63.32°W) have exited dormancy slightly early as a result of warmer temperatures but do not appear to have begun producing a second generation. Thus the life history responses of the same species in different parts of the Atlantic basin are likely to depend on a multitude of factors. It is easy to rationalize that increased periods during which development and reproduction as a result of increased temperature can lead to enhanced regional productivity, but the overall response will be dependent on the composition of the community in different parts of the Atlantic basin.

Batchelder et al. (2012) examined zooplankton abundance and biomass time series from more than 100 sites across the world ocean and found significant scales of regional coherence that extended to ~3000 km, similar to the spatial scales of environmental (e.g., sea surface temperature) synchrony which is indicative of bottom-up control of zooplankton productivity. Batchelder et al. (2012) noted a persistent decline in plankton abundance in the eastern Atlantic whereas populations demonstrated mostly decadal scale oscillation throughout much of the western Atlantic, although they noted a general decline on Georges Bank and in adjacent areas. Head and Pepin (2010b) noted that phytoplankton abundance on the Newfoundland and Scotian Shelf was generally higher in the 1990s and 2000s relative to the period from 1960 to the late 1970s. Corresponding patterns of variations in zooplankton abundance were not as clear, with modest but variable increases in key zooplankton taxa on the Scotian Shelf and off southern Newfoundland, which they attributed partly to changes in Arctic outflow, but not on the Grand Banks. More recently, total copepod abundance on the Newfoundland Shelf has been increasing since 1999, whereas it has been declining on the Scotian Shelf, with copepod numbers in the Gulf of St. Lawrence exhibiting an oscillatory pattern that started with a decline followed by a moderate increase in the mid-2000s. These short term patterns of variation cannot be attributed simply to bottom-up forcing because temperatures, and most other environmental indicators, have been on an upward (or mechanistically correlated downward) trend during the same period.

These differing trends point to the potential for differences in the influence of top-down regulation on regional zooplankton abundance. Shackell et al. (2010) highlighted alternating patterns of abundance between adjacent trophic levels from phytoplankton to piscivorous fish in most areas from the Scotian Shelf to the mid-Atlantic Bight. In the case of zooplankton, high biomass of planktivorous fish (e.g., herring, mackerel) can result in a decline in perceived abundance of zooplankton whereas zooplankton can be associated with low levels of phytoplankton abundance when planktivores have a more limited impact on zooplankton standing stocks. As a result, there may be a close link between the biomass of lower trophic levels and environmental drivers when upper trophic levels are at low levels of abundance, but the influence of climatic factors may decline as the potential for top-down control increases when fish populations become more plentiful. One can therefore infer that the projected changes in the abundance of lower trophic levels as a result of climate change may be dependent on the initial "state" of the regional ecosystems.

We can anticipate that until the influence of climate change in the western Atlantic becomes fully apparent, that a balance between short-term environmental fluctuations and changes in food web structure will likely continue to determine the abundance of zooplankton. Currently, stocks of herring and mackerel on the Scotian Shelf and Gulf of St Lawrence are at relatively elevated levels of abundance that may have resulted in declines in the biomass of zooplankton in those systems. In contrast, stocks of capelin and sand lance on the Newfoundland Shelf and Grand Banks are at low levels, compared with the higher densities that existed in the 1970s and 1980s, which may have allowed zooplankton biomass to increase during the last two decades. Once these stocks start to recover, however, zooplankton standing stocks may start to decline once again. Because the relative importance of top-down control on zooplankton populations is likely to vary with the state of forage fish populations, it is important not to equate trends in abundance directly with overall secondary production. Zooplankton production potential is directly linked to primary productivity but the transfer of energy into metazoan zooplankton will depend on the relative amount of energy funnelled through the microbial loop and the efficiency of copepods to feed on different autotrophs and micro-heterotrophs.

3.3.4 Changes in Circulation and Influence on Community Structure

Zooplankton distributions in the World Oceans are highly constrained by environmental conditions (Longhurst, 2007). Changes in ocean circulation will have a direct influence on the distribution of micro- and mesozooplankton species because despite some ability to control their horizontal position through the interaction between vertical migration and differences in current direction and strength with depth, most zooplankton are greatly influenced by transport. However, the effects of complexity and variability in regional circulation can often be most effectively detected by changes in community structure because the environmental and biological limits that govern the occurrence of individual species are rarely known (or defined in a quantitative or semi-quantitative manner), with some notable exceptions (e.g., *C. finmarchicus*).

Analyses of variability of zooplankton community structure have been limited in the Atlantic LAB. Huntley et al. (1983) provided an overview of zooplankton in Davis Strait and the Northern Labrador Sea; Head et al. (2003) considered patterns of variation across the southern Labrador Sea (AR7W line); Pepin et al. (2011b) summarized information for the Newfoundland and Labrador Shelves, Grand Banks, and western Labrador Sea; and Tremblay and Roff (1983) carried out an analysis for the Scotian Shelf. Analyses for the Gulf of St. Lawrence have been limited to portions of the area and often to a subset of the species present (e.g., Plourde et al., 2002, Descroix et al., 2005). Throughout much of the Atlantic LAB, zooplankton communities demonstrate a strong and repeatable association with hydrographic features and unpublished analyses of the spring and autumn collections from the 14 AZMP standard sections indicates a high degree of spatial organization that is regional, latitudinal and across isobaths.

Zooplankton communities in and adjacent to the Labrador Sea have demonstrated a high degree of spatial structure that appears to be greatly constrained by the effects of the West Greenland, Baffin Island and Labrador Currents. Head et al. (2003) found a strong association between communities and hydrographic features across the central Labrador Sea, with shelf, slope and open ocean communities demonstrating repeatable, albeit variable, spatial structuring. Pepin et al. (2011b) found a strong cross shelf gradient in both physical and biological features, with a consistent pattern of water mass associations among species among all seasons. Unpublished analyses (P. Pepin, C. Johnson, M. Harvey) of zooplankton community structure for the NLS, GSL and SS also reveal strong separation of communities in relation to bathymetry, but there is considerably more variability in this association on the SS than in the two other regions. The high degree of variability in community structure on the SS is consistent with the observations of Tremblay and Roff (1983), who could explain only a small fraction of the spatial variation in community structure relative to that observed in the NLS by Pepin et al. (2011b) and which is likely attributable to the effects of greater variations in regional circulation that is apparent on the SS when contrasted with the NLS. Slope water intrusions, Gulf Stream meanders and complex bathymetry result in considerable variability in water mass composition on the Scotian Shelf that results in a high degree of mixing that is reflected in considerable variability in zooplankton composition (C. Johnson, pers. comm.). Together, the findings of these studies indicate that variability in water mass composition (and hence currents) is likely to be reflected in variability in zooplankton distributions and composition, but the degree to which we have predictive capabilities is likely to be inversely related to the degree of mixing among water masses.

Trends and projections provided by the oceanographers (Loder et al., 2013) indicate that in the short term there may be possible changes in positions and strength of major ocean currents (Gulf Stream, Labrador Current, Arctic outflow, Atlantic Meridional Overturning Circulation (AMOC)), but these are likely to be dominated by natural variability rather than anthropogenic change over the next decade. On the longer term, the magnitudes are uncertain and likely comparable to decadal variability, but net effects on regional ocean climate could be substantial. There will likely be a northward shift of the Gulf Stream and increased (reduced) influence of subtropical (subpolar) slope water that will influence the Scotian Shelf, but the magnitude is uncertain and may be comparable to decadal variability. The Newfoundland-Labrador Shelf is moderately likely to see an intensification of Labrador Current and contraction of subpolar gyre while there will likely be a reduction in the strength of Atlantic Meridional Overturning Circulation in the Labrador Sea. It is also likely that there will be a reduction in the volume transport of freshwater through the Canadian Arctic Archipelago but an intensification of buoyancy driven circulation resulting in increased Greenland glacial melt. In the Gulf of St. Lawrence, there will likely be changes in circulation associated with remote influences from changes in Gulf Stream (affecting deep waters) and Labrador Current (affecting all depths). As a result of these anticipated changes, we can expect an expansion of the communities associated with the West Greenland and Labrador Currents around the Labrador Sea while there will likely be an expansion of the warm water communities in the southwestern portions of the SS of the Atlantic LAB. The GSL will likely see greater variability (and uncertainty) as a result of the remote influences of the Gulf Stream and Labrador Current as well as increases in the freshwater discharge and possible changes in the timing of the peak outflow.

How the changes in zooplankton distribution and community structure will affect regional productivity is uncertain. More extensive habitats (water masses) suitable for large calanoid copepods are likely to provide greater production potential for these important elements of regional marine ecosystems such as the

NLS. This is not to say that increased occurrence of smaller zooplankton that are associated with warmer water masses will be detrimental to production in the southern parts of the Atlantic Lab (GSL, SS) because regions further south, such as the GoM, are also highly productive. Warmer temperatures and prolonged production owing to a protracted seasonal cycle are likely to have a considerable effect on regional productivity, but how this compares to changes resulting from alterations in ocean circulation cannot be assessed based on the available information.

3.4. CONCLUSION: COMMUNITY STRUCTURE AND LINK TO THERMAL REGIME AND CONSEQUENCES FOR TRANSFER TO HIGHER TROPHIC LEVELS

Temperature increase is the primary environmental variable to change in response to climate change resulting from anthropogenic inputs to the atmosphere. Changes in atmospheric forcing, stratification, ice melt/freshwater input are all secondary outcomes that interact with temperature increases through complex feedbacks. All these factors are known to influence the distribution and production potential of lower trophic levels. Some effects may be viewed as positive from a societal perspective while others may be considered as negative. From the perspective of Climate Change Adaptation for Fisheries and Oceans Canada, key considerations are how these effects will alter ecosystem functions and how they may impact the regional productivity and sustainability of the marine ecosystems for which the Government of Canada has mandated responsibilities.

Relatively simple scenarios for pathways of effects are appealing because they often represent a simple chain of driver-response outcomes that can easily be generalized. In the case of lower trophic levels in marine ecosystems, a number of the general principles have been used to infer potential changes in regional productivity: [1] broad scale biogeographic patterns in community and foodweb structure of both phyto- and zooplankton (Li); [2] allometric (weight-dependent) and temperature-dependent relationship of physiological and ecological processes (Silvert and Platt, 1978); and [3] trophic cascades that have formed the basis of the simplest estimates of ecosystem production potential (Ryther, 1969, Ware and Thomson, 2005) and which have been demonstrated in temperate-boreal freshwater systems (e.g., Carpenter et al., 2001). However, the predictions from such basic relationships have seldom been contrasted with reasonably realistic regional models of biophysical or foodweb interactions to determine if the temporal changes in ecosystem properties are mirrored by simulated forecasts, let alone being contrasted with observational series. Consideration of the ability of any general principle or reductionist simulation to predict spatial-temporal changes in lower trophic levels is critical because comparisons among different forecasting tools have demonstrated that a broad range of outcomes can be predicted depending on which approach is taken and the underlying assumptions (Dadou et al., 2004, Anderson et al., 2010, Kriest et al., 2010, Prowe et al., 2012). As a result of the limited knowledge of the drivers and trophic interactions that affect the potential productivity of regional shelves in the Atlantic LAB, forecasts of the potential impact of climate change have moderate to high levels of uncertainty in the magnitude of the change, but the probability of the impacts are generally moderate (41-60%) to likely (61-80%) over the longer term because some of the underlying relationships are sufficiently strong that conditions outside the range of previous observations are likely to occur.

The key inferences concerning the potential risks to factors that are of significance to Fisheries and Oceans Canada resulting from climate change in both the intermediate (10–20 years) and long term (50 years) are:

- Projected increases in water temperatures and ocean stratification (and its effect on nutrient distribution) will favor smaller phytoplankton cells and zooplankton communities. A decrease in plankton size is likely to favour a larger microbial loop as well as predation by smaller zooplankton, resulting in an increase in food chain length that decreases the efficiency of energy flow from the primary producers to the top predators. This may result in a decrease in fishery catch potential. This effect may be counterbalanced to some extent if phytoplankton production in northern latitudes increases by mid-century as a result of a longer growing season.
- Temperature determines the rates of most metabolic processes in poikilotherms, but the balance between growth and mortality rates remains unclear because of a lack of knowledge concerning the temperature dependency of the latter. We can expect that growth and development rates will increase in nearly all components of the lower trophic levels, and the greatest impact may be on life history patterns as a result of prolonged seasonal growth that can result in increased productivity.
- Changes in water mass distributions and temperature fields determine the distribution of most plankton in the western Atlantic. Changes in Arctic outflow are likely to affect the export of cold water species toward southern areas on the short term, but on the long term these elements will not be self-sustaining elements of the food web at their southern extremes. Even with a 2 to 4 °C increase in surface temperature, most species of phytoplankton and zooplankton in the northwest Atlantic will be within their normal physiological range. Areas of the Scotian Shelf and Gulf of St. Lawrence should experience a gradual shift toward warmer water species, which are generally smaller in size, but large calanoid copepods will remain as important elements of the regional ecosystems and their productivity may be enhanced on parts of the Newfoundland Shelf. We can expect a decrease in the role of cold water species in both these

regions, but the net impact of changes in species distribution in the western Labrador Sea is unclear.

- Higher temperatures and increased stratification will likely favour a greater occurrence and influence of dinoflagellates and coccolithophores throughout the western Atlantic. The relative importance of diatoms may be reduced because of the reduced availability of nutrients.
- Higher temperature and reduced nutrient availability may favour an increased occurrence of harmful algal blooms, particularly in southerly and coastal areas. Higher thermal regimes may allow an enhanced distributional range of some species onto the Newfoundland shelf, either through introductions or as a result of natural range expansion. The importance of such events may be compounded or enhanced by anthropogenic influences, particularly in areas influenced by high population density and nutrient input.
- Higher temperatures will likely lead to changes in the timing of occurrence of species closely linked with the seasonal temperature cycle. Taxa with peak abundance in the spring will occur earlier in the year whereas species that peak in abundance in the autumn will generally occur later in the year. Whether species adapt to changes in the seasonal cycle, and how they do so, will significantly affect the impact on regional productivity, but this is a topic for which there is very limited knowledge. Taxa that can survive during periods of lower nutrient/prey abundance, which normally occur between the spring and autumn blooms, will likely benefit from climate change, but species that enter prolonged periods of dormancy may be subjected to increased competition from taxa that can take advantage of the longer "productive" season.
- Reduced ice cover, higher temperature and an earlier onset of stratification will likely result in an earlier onset of the spring phytoplankton bloom, and a longer growth season may lead to a later autumn bloom in temperate parts of the region. Analysis of satellite imagery indicates that most parts of the continental shelf from the southern Scotian Shelf to coastal Labrador may respond in synchrony to long-term changes in environmental conditions. However, deep basin (e.g., Labrador Sea) and more northerly areas, where light limitation may play a significant role, may not respond to the same extent to the effects of climate change.
- The earlier increase above threshold temperatures and in the onset of the spring phytoplankton bloom will likely allow *Calanus finmarchicus* populations to achieve a prolonged production period under climate change throughout most of the western Atlantic basin. There will likely be a detrimental effect in areas

where summer surface temperatures exceed physiological thresholds (e.g., southern SS, parts of GSL), but the net effect will depend very much on the seasonal rate of warming in those areas. Because this species is a cornerstone in the diet of many planktivorous fish, any change in population abundance will likely have an impact on higher trophic levels. Although we anticipate changes in the frequency of occurrence in areas associated with the SS, and possibly GSL, the magnitude of the decline should not be as extreme as in the Northeast Atlantic where a sister species has demonstrated increased abundance and occurrence. There will likely be enhanced production off Newfoundland and in the Labrador Sea.

- The response of phytoplankton and zooplankton to changes in environmental forcing will depend greatly on the status of the remainder of the food web. Evidence of trophic cascades appears to be substantial for the SS and areas of Georges Bank/GoM, but less so in the GSL and Newfoundland Shelf. When the abundance of planktivorous fish is low, the abundance of lower trophic levels is more likely to be closely associated with changes in the physical environment than when predation pressure from forage fish is more substantial.

3.5 REFERENCES

Agawin, N.S.R., Duarte, C.M., and Agustí, S. 2000. Nutrient and temperature control of the contribution of picoplankton to phytoplankton biomass and production. Limnology and Oceanography 45: 591–600.

Anderson, D.M., Cembella, A.D., and Hallegraeff, G.M. 2012. Progress in understanding harmful algal blooms: paradigm shifts and new technologies for research , monitoring , and management. Annual Review of Marine Science 4: 143–176. doi: 10.1146/annurev-marine-120308-081121.

Anderson, T.R., Gentleman, W.C. and Sinha, B. 2010. Influence of grazing formulations on the emergent properties of a complex ecosystem model in a global ocean general circulation model. Progress in Oceanography, 87, 201-213. 10.1016/j.pocean.2010.06.003

Antoine, D., Morel, A., Gordon, H.R., Banzon, V.F., and Evans, R.H. 2005. Bridging ocean color observations of the 1980s and 2000s in search of long-term trends. Journal of Geophysical Research 110: C06009. doi: 10.1029/2004JC002620.

Ardyna, M., Gosselin, M., Michel, C., Poulin, M., and Tremblay, J.-E. 2011. Environmental forcing of phytoplankton community structure and function in the Canadian High Arctic: contrasting oligotrophic and eutrophic regions. Marine Ecology Progress Series 442: 37–57. doi: 10.3354/meps09378.

Arrigo, K.R., Perovich, D.K., Pickart, R.S., Brown, Z.W., Dijken, G.L.V., Lowry, K.E., Mills, M.M., Palmer, M.A., Balch, W.M., Bahr, F., Bates, N.R., Benitez-Nelson, C., Bowler, B., Brownlee, E., Ehn, J.K., Frey, K.E., Garley, R., Laney, S.R., Lubelczyk, L., Mathis, J., Matsuoka, A., Mitchell, B.G., Moore, G.W.K., Ortega-Retuerta, E., Pal, S., Polashenski, C.M., Reynolds, R.A., Schieber, B., Sosik, H.M., Stephens, M., and

Swift, J.H. 2012. Massive phytoplankton blooms under Arctic sea ice. Science 336: 1408.

Arrigo, K.R., van Dijken, G., and Pabi, S. 2008. Impact of a shrinking Arctic ice cover on marine primary production. Geophysical Research Letters 35: 1–6. doi: 10.1029/2008GL035028.

Atkinson, D., Ciotti, B.J., and Montagnes, D.J.S. 2003. Protists decrease in size linearly with temperature: ca. 2.5% °C-1. Proceedings of the Royal Society B. Biological sciences 270: 2605–2611. doi: 10.1098/rspb.2003.2538.

Azetsu-Scott, K., Clarke, A., Falkner, K., Hamilton, J., Jones, E.P., Lee, C., Petrie, B., Prinsenberg, S., Starr, M., and Yeats, P. 2010. Calcium carbonate saturation states in the waters of the Canadian Arctic Archipelago and the Labrador Sea. Journal of Geophysical Research 115. doi: 10.1029/2009JC005917.

Bakun, A. 1990. Global Climate Change and Intensification of Coastal Ocean Upwelling. Science 247: 198–201.

Batchelder, H.P., Mackas, D.L. and O'Brien, T.D. 2012. Spatial-temporal scales of synchrony in marine zooplankton biomass and abundance patterns: a world-wide comparison. Progress in Oceanography, 97-100, 15-30. 10.1016/j.pocean.2011.11.010

Bates, S., Bird, C., de Freitas, A., Foxall, R., Gilgan, M., Hanic, L., Johnson, G., McCulloch, A., Odense, P., Pocklington, R., Quilliam, M., Sim, P., Smith, J., Subba Rao, D., Todd, E., Walter, J., and Wright, J. 1989. Pennate diatom *Nitzschia pungens* as the primary source of domoic acid, a toxin in shellfish from eastern Prince Edward Island, Canada. Canadian Journal of Fisheries and Aquatic Science 46: 1203–1215.

Beardall, J., and Stojkovic, S. 2006. Microalgae under Global Environmental Change: Implications for Growth and Productivity, Populations and Trophic Flow. Science Asia 32: 1–10. doi: 10.2306/scienceasia1513-1874.2006.32(s1).001.

Beardall, J., Stojkovic, S., and Larsen, S. 2009. Living in a high CO_2 world: impacts of global climate change on marine phytoplankton. Plant Ecology and Diversity 2: 191–205. doi: 10.1080/17550870903271363.

Beaufort, L., Probert, I., de Garidel-Thoron, T., Bendif, E.M., Ruiz-Pino, D., Metzl, N., Goyet, C., Buchet, N., Coupel, P., Grelaud, M., Rost, B., Rickaby, R.E.M., and de Vargas, C. 2011. Sensitivity of coccolithophores to carbonate chemistry and ocean acidification. Nature 476: 80–83. doi: 10.1038/nature10295.

Beaugrand, G. 2009. Decadal changes in climate and ecosystems in the North Atlantic Ocean and adjacent seas. Deep Sea Research Part II: Topical Studies in Oceanography 56: 656–673. doi: 10.1016/j.dsr2.2008.12.022.

Beaugrand, G. 2012. Unanticipated biological changes and global warming. Marine Ecology Progress Series 445: 293–301. doi: 10.3354/meps09493.

Beaugrand, G., Luczak, C., and Edwards, M. 2009. Rapid biogeographical plankton shifts in the North Atlantic Ocean. Global Change Biology 15: 1790–1803. doi: 10.1111/j.1365-2486.2009.01848.x.

Behrenfeld, M. 2011. Biology: Uncertain future for ocean algae. Nature Climate Change 1: 33–34. doi: 10.1038/nclimate1069.

Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M., and Boss, E.S. 2006. Climate-driven trends in contemporary ocean productivity. Nature 444: 752–755. doi: 10.1038/nature05317.

Blasco, D., Levasseur, M., Bonneau, E., Gelinas, R., Packard, T.T. 2003. Patterns of paralytic shellfish toxicity in the St. Lawrence region in relationship with the abundance and distribution of *Alexandrium tamarense*. Scientia Marina 67: 261-278.

Bode, A., Hare, J., Li, W.K.W., Morán, X.A.G., and Valdes, L. 2011. Chlorophyll and primary production in the North Atlantic. In Ices Status Report on climate change in the North Atlantic. (P.C. Reid and L. Valdés eds). ICES Cooperative Research Report No. 310: 77-102.

Bopp, L., Aumont, O., Cadule, P., Alvain, S., Gehlen, M. 2005. Response of diatoms distribution to global warming and potential implications: A global model study. Geophysical Research Letters 32: 2–5. doi: 10.1029/2005GL023653.

Bopp, L., Monfray, P., Aumont, O., Dufresne, J., Le Treut, H., Madec, G., Terray, L., and Orr, J.C. 2001. Potential impact of climate change on marine export production. Global Biogeochemical Cycles 15: 81–99. Available from http://www.up.ethz.ch/education/biogeochem_cycles/reading_list/bopp_gbc_01.pdf.

Boyce, D.G., Lewis, M.R., and Worm, B. 2010. Global phytoplankton decline over the past century. Nature 466: 591–6. doi: 10.1038/nature09268.

Boyd, P.W. 2011. Beyond ocean acidification. Nature Geoscience 4: 273–274. doi: 10.1038/ngeo1150.

Boyd, P.W., Strzepek, R., Fu, F., and Hutchins, D.A. 2010. Environmental control of open-ocean phytoplankton groups: Now and in the future. Limnology and Oceanography 55: 1353–1376. doi: 10.4319/lo.2010.55.3.1353.

Brown, C.W. 1995. Global distribution of coccolithophore blooms. Oceanography 8: 59–60.

Brown, C.W., and Yoder, J.A. 1994. Coccolithophorid blooms in the global ocean. Journal of Geophysical Research 99: 7467–7482.

Campbell, R.W. and Head, E.J.H. 2000. Egg production rates of *Calanus finmarchicus* in the western North Atlantic: effect of gonad maturity, female size, chlorophyll concentration, and temperature. Canadian Journal of Fisheries and Aquatic Sciences, 57, 518-529.

Carpenter, S.R., Cole, J.J., Hodgson, J.R., Kitchell, J.F., Pace, M.L., Bade, D., Cottingham, K.L., Essington, T.E., Houser, J.N. and Schindler, D.E. 2001. Trophic cascades, nutrients, and lake productivity: whole-lake experiments. Ecological Monographs, 71, 163-186. 10.1890/0012-9615(2001)071[0163:tcnalp]2.0.co;2

Chavez, F.P., Messié, M., and Pennington, J.T. 2011. Marine Primary Production in Relation to Climate Variability and Change. Annual Review of Marine Science 3: 227–260. doi: 10.1146/annurev.marine.010908.163917.

Craig, J.D.C., and Colbourne, E.B. 2002. Trends in Stratification on the inner Newfoundland Shelf. Canadian Science Advisory Secretariat Research Document 2002/071.

Craig, J.D.C., Colbourne, E.B., and Maillet, G.L. 2001. Preliminary studies of density stratification and fluorescence on the Newfoundland Shelf. Canadian Science Advisory Secretariat Research Document 2001/085.

Dadou, I., Evans, G. and Garcon, V. 2004. Using JGOFS in situ and ocean color data to compare biogeochemical models and estimate their parameters in the subtropical

North Atlantic Ocean. Journal of Marine Research, 62, 565-594. 10.1357/0022240041850057

Daufresne, M., Lengfellner, K., and Sommer, U. 2009. Global warming benefits the small. Proceedings of the National Academy of Sciences of the United States of America 106: 12788–12793.

Descroix, A., Harvey, M., Roy, S. and Galbraith, P.S. 2005. Macrozooplankton community patterns driven by water circulation in the St. Lawrence marine system, Canada. Marine Ecology Progress Series, 302, 103-119. 10.3354/meps302103

Doney, S.C. 2006. Plankton in a warmer World. Nature 444: 695–696. doi: 10.1029/2003GB002134.

Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., Rabalais, N.N., Sydeman, W.J., and Talley, L.D. 2012. Climate Change Impacts on Marine Ecosystems. Annual Review of Marine Science 4: 11–37. doi: 10.1146/annurev-marine-041911-111611.

Edwards, M. and Richardson, A.J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature, 430, 881-884. 10.1038/nature02808

Edwards, M., and Richardson, A.J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430: 881–884.

Edwards, M., Johns, D.G., Leterme, S., Svendsen, E., and Richardson, A. 2006. Regional climate change and harmful algal blooms in the northeast Atlantic. Limnology and Oceanography 51: 820–829.

Edwards, M., Reid, P., and Planque, B. 2001. Long-term and regional variability of phytoplankton biomass in the Northeast Atlantic (1960–1995). ICES Journal of Marine Science 58: 39–49. doi: 10.1006/jmsc.2000.0987.

Eilertsen, H.C., Sandberg, S., and Tollefsen, H. 1995. Photoperiodic control of diatom spore growth: a theory to explain the onset of phytoplankton blooms. Marine Ecology Progress Series 116: 303–307.

Falkowski, P.G., and Oliver, M.J. 2007. Mix and match: how climate selects phytoplankton. Nature reviews. Microbiology 5: 813–819. doi: 10.1038/nrmicro1751.

Feely, R.A., Doney, S.C., and Cooley, S.R. 2009. Ocean Acidification: Present Conditions and Future Changes in a High-CO_2 World. Oceanography 22: 36–47. doi: 10.5670/oceanog.2009.106.

Finkel, Z.V., Beardall, J., Flynn, K.J., Quigg, A., Rees, T.A., and Raven, J.A. 2010. Phytoplankton in a changing world: cell size and elemental stoichiometry. Journal of Plankton Research 32: 119–137. doi: 10.1093/plankt/fbp098.

Galbraith, P.S., Chassé, J., Gilbert, D., Larouche, P., Brickman, D., Pettigrew, B., Devine, L., Gosselin, A., Pettipas, R.G. and Lafleur, C. 2012. Physical Oceanographic Conditions in the Gulf of St. Lawrence in 2011 - Conditions océanographiques physiques dans le golfe du Saint-Laurent en 2011. Canadian Science Advisory Secretariat Research Document 2012/023. iii, 85pp.

Gao, K., Xu, J., Gao, G., Li, Y., Hutchins, D. a., Huang, B., Wang, L., Zheng, Y., Jin, P., Cai, X., Häder, D.-P., Li, W., Xu, K., Liu, N., and Riebesell, U. 2012. Rising CO_2 and increased light exposure synergistically reduce marine primary productivity. Nature Climate Change 2: 519–523. doi: 10.1038/nclimate1507.

Greenan, B., Harrison, G., Yashayaev, I., Azetsu-Scott, K., Head, E., Li, W., and Loder, J. 2009. Physical, chemical, and biological conditions in the Labrador Sea in 2009. doi: 10.3137/ao.450302.I.

Greene, C.H., and Pershing, A.J. 2007. Oceans. Climate drives sea change. Science 315: 1084–5. doi: 10.1126/science.1136495.

Gregg, W.W., and Casey, N.W. 2007. Modeling coccolithophores in the global oceans. Deep Sea Research Part II: Topical Studies in Oceanography 54: 447–477. doi: 10.1016/j.dsr2.2006.12.007.

Gregg, W.W., Casey, N.W., and McClain, C.R. 2005. Recent trends in global ocean chlorophyll. Geophysical Research Letters 32: L03606. doi: 10.1029/2004GL021808.

Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: A formidable predictive challenge. Journal of Phycology 46: 220–235. doi: 10.1111/j.1529-8817.2010.00815.x.

Han, G., E. Colbourne, P. Pepin and R. Tang. 2013. Statistical projections of physical oceanographic variables over the Newfoundland and Labrador Shelf. Ch.6 (p.73-84) In: Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p.

Harrison, W.G., and Li, W.K.W. 2008. Phytoplankton Growth and Regulation in the Labrador Sea: Light and Nutrient Limitation. Journal of Northwest Atlantic Fisheries Science 39: 71–82. doi: 10.2960/J.v39.m592.

Hays, G.C., Richardson, A.J., and Robinson, C. 2005. Climate change and marine plankton. Trends in Ecology and Evolution 20: 337–344. doi: 10.1016/j.tree.2005.03.004.

Head, E., and Pepin, P. 2010a. Monitoring changes in phytoplankton abundance and composition in the Northwest Atlantic: a comparison of results obtained by continuous plankton recorder sampling and colour satellite imagery. Journal of Plankton Research 32: 1649–1660. doi: 10.1093/plankt/fbq120.

Head, E.J.H. and Pepin, P. 2010b. Spatial and inter-decadal variability in plankton abundance and composition in the Northwest Atlantic (1958-2006). Journal of Plankton Research, 32, 1633-1648. 10.1093/plankt/fbq090

Head, E.J.H., and Pepin, P. 2010c. Spatial and inter-decadal variability in plankton abundance and composition in the Northwest Atlantic (1958-2006). Journal of Plankton Research 32: 1633–1648. doi: 10.1093/plankt/fbq090.

Head, E.J.H., and Sameoto, D.D. 2007. Inter-decadal variability in zooplankton and phytoplankton abundance on the Newfoundland and Scotian shelves. Deep Sea Research Part II 54: 2686–2701. doi: 10.1016/j.dsr2.2007.08.003.

Head, E.J.H., Harris, L.R. and Yashayaev, I. 2003. Distributions of Calanus spp. and other mesozooplankton in the Labrador Sea in relation to hydrography in spring and summer (1995-2000). Progress in Oceanography, 59, 1-30. 10.1016/s0079-6611(03)00111-3

Helaouet, P., Beaugrand, G. and Reid, P.C. 2011. Macrophysiology of *Calanus finmarchicus* in the North Atlantic Ocean. Progress in Oceanography, 91, 217-228. 10.1016/j.pocean.2010.11.003

Hirst, A. and Bunker, A.J. 2003. Growth of marine planktonic copepods: Global rates and patterns in relation to chlorophyll a, temperature, and body weight. Limnology and Oceanography, 48, 1988-2010.

Huntley, M., Strong, K.W. and Dengler, A.T. 1983. Dynamics and Community Structure of Zooplankton in the Davis Strait and Northern Labrador Sea. Arctic, 36, 143-161.

Iglesias-Rodriguez, M.D., Halloran, P.R., Rickaby, R.E.M., Hall, I.R., Colmenero-hidalgo, E., Gittins, J.R., Green, D.R.H., Tyrrell, T., Gibbs, S.J., Dassow, P.V., Rehm, E., Armbrust, E.V., and Boessenkool, K.P. 2008. Phytoplankton calcification in a high-CO_2 world. Science 320: 336–340. doi: 10.1126/science.1154122.

Irwin, A.J., Nelles, A.M., and Finkel, Z.V. 2012. Phytoplankton niches estimated from field data. Limnology and Oceanography 57: 787–797. doi: 10.4319/lo.2012.57.3.0787.

Ji, R., Davis, C.S., Chen, C., Townsend, D.W., Mountain, D.G., and Beardsley, R.C. 2007a. Modeling the influence of North Atlantic freshening on phytoplankton dynamics in the Nova Scotian Shelf and Gulf of Maine region. ICES CM Document 2007/B:11.

Ji, R., Davis, C.S., Chen, C., Townsend, D.W., Mountain, D.G., and Beardsley, R.C. 2007b. Influence of ocean freshening on shelf phytoplankton dynamics. Geophysical Research Letters 34: L24607. doi: 10.1029/2007GL032010.

Ji, R., Davis, C.S., Chen, C., Townsend, D.W., Mountain, D.G., and Beardsley, R.C. 2008. Modeling the influence of low-salinity water inflow on winter-spring phytoplankton dynamics in the Nova Scotian Shelf-Gulf of Maine region. Journal of Plankton Research 30: 1399–1416. doi: 10.1029/2007GL032010.

Ji, R., Edwards, M., Mackas, D.L., Runge, J.A., and Thomas, A.C. 2010. Marine plankton phenology and life history in a changing climate: current research and future directions. Journal of Plankton Research 32: 1355–1368. doi: 10.1093/plankt/fbq062.

Johns, D.G., Edwards, M., and Batten, S.D. 2001. Arctic boreal plankton species in the Northwest Atlantic. Canadian Journal of Fisheries and Aquatic Science 58: 2121–2124. doi: 10.1139/cjfas-58-11-2121.

Johns, D.G., Edwards, M., Richardson, A., and Spicer, J.I. 2003. Increased blooms of a dinoflagellate in the NW Atlantic. Marine Ecology Progress Series 265: 283–287. doi: 10.3354/meps265283.

Kahru, M., Brotas, V., Manzano-Sarabia, M., and Mitchell, B.G. 2011. Are phytoplankton blooms occurring earlier in the Arctic? Global Change Biology 17: 1733–1739. doi: 10.1111/j.1365-2486.2010.02312.x.

Keeling, R.A. 2010. Ocean Acidification Unprecedented , Unsettling. Science 328: 1500–1501.

Kriest, I., Khatiwala, S. and Oschlies, A. 2010. Towards an assessment of simple global marine biogeochemical models of different complexity. Progress in Oceanography, 86, 337-360. 10.1016/j.pocean.2010.05.002

Kroeker, K.J., Kordas, R.L., Crim, R.N., and Singh, G.G. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecology letters 13: 1419–1434. doi: 10.1111/j.1461-0248.2010.01518.x.

Leterme, S.C., and Pingree, R.D. 2007. Structure of phytoplankton (Continuous Plankton Recorder and SeaWiFS) and impact of climate in the Northwest Atlantic Shelves. Ocean Science 3: 105–116.

Leterme, S.C., Edwards, M., Seuront, L., Attrill, M.J., Reid, P.C., and John, A.W.G. 2005. Decadal basin-scale changes in diatoms, dinoflagellates, and phytoplankton color across the North Atlantic. Limnology and Oceanography 50: 1244–1253.

Li, W.K.W., and Harrison, W.G. 2008. Propagation of an atmospheric climate signal to phytoplankton in a small marine basin. Limnology and Oceanography 53: 1734–1745. doi: 10.4319/lo.2008.53.5.1734.

Li, W.K.W., Harrison, W.G., and Head, E.J.H. 2006a. Coherent assembly of phytoplankton communities in diverse temperate ocean ecosystems. Proceedings of the Royal Society B: Biological Sciences 273: 1953–1960. doi: 10.1098/rspb.2006.3529.

Li, W.K.W., Harrison, W.G., and Head, E.J.H. 2006b. Coherent sign switching in multiyear trends of microbial plankton. Science 311: 1157–60. doi: 10.1126/science.1122748.

Li, W.K.W., McLaughlin, F.A., Lovejoy, C., and Carmack, E.C. 2009. Smallest algae thrive as the Arctic Ocean freshens. Science 326: 539.

Longhurst, A. 2007. Ecological geography of the sea. 2nd edition. Academic Press, Burlington, Massachusetts.

Longhurst, A., Sathyendranath, S., Platt, T., and Caverhill, C. 1995. An estimate of global primary production in the ocean from satellite radiometer data. Journal of Plankton Research 17: 1245–1271. doi: 10.1093/plankt/17.6.1245.

Mackas, D.L. 2011. Does blending of chlorophyll data bias temporal trend? Nature 472: E4–E5. doi: 10.1038/nature09952.

Mackas, D.L., Greve, W., Edwards, M., Chiba, S., Tadokoro, K., Eloire, D., Mazzocchi, M.G., Batten, S., Richardson, A.J., Johnson, C., Head, E., Conversi, A. and Peluso, T. 2012. Changing zooplankton seasonality in a changing ocean: Comparing time series of zooplankton phenology. Progress in Oceanography, 97-100, 15-30. 10.1016/j.pocean.2011.11.005

Maillet, G. 2010. Seasonality of phytoplankton abundance derived from satellite data in the northwest Atlantic during 1998 to 2009. NAFO SCR Doc. 10/13.

Maillet, G. and Pepin, P. 2005. Timing of plankton cycles on the Newfoundland Grand Banks: potential influence of climate change. NAFO SCR Doc. 05/12, Serial N5091. 12pp.

Maillet, G., Pepin, P., Johnson, C., Harrison, G., Head, E., Spry, J., Pauley, K., Caverhill, C., Maass, H., Kennedy, M., Porter, C., Yashayaeva, I., Casault, B., Fraser, S., Shears, T., and Redmond, G. 2011. Biological and chemical oceanographic conditions on the Newfoundland and Labrador Shelf, Grand Banks, Scotian Shelf, and the Gulf of Maine during 2010. NAFO SCR Doc. 11/013.

Maillet, G.L., and Pepin, P. 2005. Timing of plankton cycles on the Newfoundland Grand Banks: Potential influence of climate change. NAFO SCR Doc. 05/12.

Martin, J.L., Hanke, A.R., and LeGresley, M.M. 2009. Long term phytoplankton monitoring, including harmful algal blooms, in the Bay of Fundy, eastern Canada. Journal of Sea Research 61: 76–83. Elsevier B.V. doi: 10.1016/j.seares.2008.05.011.

Martin, J.L., Page, F.H., Hanke, A., Strain, P.M., and LeGresley, M.M. 2005. *Alexandrium fundyense* vertical distribution patterns during 1982, 2001 and 2002 in the offshore Bay of Fundy, eastern Canada. Deep Sea Research Part II: Topical Studies in Oceanography 52: 2569–2592. doi: 10.1016/j.dsr2.2005.06.010.

Martinez, E., Antoine, D., D'Ortenzio, F., and de Boyer Montégut, C. 2011. Phytoplankton spring and fall blooms in the North Atlantic in the 1980s and 2000s. Journal of Geophysical Research 116. doi: 10.1029/2010JC006836.

Martinez, E., Antoine, D., D'Ortenzio, F., and Gentili, B. 2009. Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. Science 326: 1253–1256. doi: 10.1126/science.1177012.

McQuatters-Gollop, A., Reid, P.C., Edwards, M., Burkill, P.H., Castellani, C., Batten, S., Gieskes, W., Beare, D., Bidigare, R.R., Head, E., Johnson, R., Kahru, M., Koslow, J.A., and Pena, A. 2011. Is there a decline in marine phytoplankton? Nature 472: E6–E7. doi: 10.1038/nature09950.

Morán, X.A.G., López-Urrutia, Á., Calvo-Díaz, A., and Li, W.K.W. 2010. Increasing importance of small phytoplankton in a warmer ocean. Global Change Biology 16: 1137–1144. doi: 10.1111/j.1365-2486.2009.01960.x.

Mudie, P.J., Rochon, A., and Levac, E. 2002. Palynological records of red tide-producing species in Canada: past trends and implications for the future. Palaeogeography, Palaeoclimatology, Palaeoecology 180: 159–186.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.-K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.-F., Yamanaka, Y., and Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437: 681–686. doi: 10.1038/nature04095.

Pepin, P., and Paranjape, M.A. 1996. Summary of biological oceanographhic variables in the Newfoundland Region. DFO Atlantic Fisheries Research Document 96/2.

Pepin, P., Maillet, G., Fraser, S., Shears, T., and Redmond, G. 2011a. Optical, chemical, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2009 and 2010. Canadian Science Advisory Secretariat Research Document 2011/074. iv + 45 p.

Pepin, P., Colbourne, E. and Maillet, G. 2011b. Seasonal patterns in zooplankton community structure on the Newfoundland and Labrador Shelf. Progress in Oceanography, 91, 273-285. doi:10.1016/j.pocean.2011.01.003

Pepin, P., G.L. Maillet, D. Lavoie and C. Johnson. 2013. Temporal trends in nutrient concentrations in the northwest Atlantic basin. Ch.10 (p.127-150) In: Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p.

Pershing, A.J., Head, E.H.J., Greene, C.H. and Jossi, J.W. 2010. Pattern and scale of variability among Northwest Atlantic Shelf plankton communities. Journal of Plankton Research, 32, 1661-1674. 10.1093/plankt/fbq058

Peterson, B.J., McClelland, J., Curry, R., Holmes, R.M., Walsh, J.E., and Aagaard, K. 2006. Trajectory shifts in the Arctic and subarctic freshwater cycle. Science 313: 1061–6. doi: 10.1126/science.1122593.

Plourde, S., Dodson, J.J., Runge, J.A. and Therriault, J.C. 2002. Spatial and temporal variations in copepod community structure in the lower St. Lawrence Estuary, Canada. Marine Ecology Progress Series, 230, 211-224.

Plourde, S., Pepin, P. and Head, E.J.H. 2009. Long-term seasonal and spatial patterns in mortality and survival of *Calanus finmarchicus* across the Atlantic Zone Monitoring Programme region, Northwest Atlantic. ICES Journal of Marine Science, 66, 1942-1958. 10.1093/icesjms/fsp167

Polovina, J.J., Howell, E. a., and Abecassis, M. 2008. Ocean's least productive waters are expanding. Geophysical Research Letters 35: 2–6. doi: 10.1029/2007GL031745.

Poulton, A.J., Adey, T.R., Balch, W.M., and Holligan, P.M. 2007. Relating coccolithophore calcification rates to phytoplankton community dynamics: Regional differences and implications for carbon export. Deep Sea Research Part II: Topical Studies in Oceanography 54: 538–557. doi: 10.1016/j.dsr2.2006.12.003.

Prowe, A.E.F., Pahlow, M., Dutkiewicz, S., Follows, M. and Oschlies, A. 2012. Top-down control of marine phytoplankton diversity in a global ecosystem model. Progress in Oceanography, 101, 1-13. 10.1016/j.pocean.2011.11.016

Regaudie-de-Gioux, A., and Duarte, C.M. 2012. Temperature dependence of planktonic metabolism in the ocean. Global Biogeochemical Cycles 26: GB101015. doi: 10.1029/2010GB003907.

Reid, P.C., and Valdés, L. 2011. ICES status report on climate change in the North Atlantic. ICES Cooperative Research Report No. 310. 262 pp.

Reid, P.C., Edwards, M., Hunt, H.G., and Warner, A.J. 1998. Phytoplankton change in the North Atlantic. Nature 391: 546.

Reid, P.C., Johns, D.G., Edwards, M., Starr, M., Poulin, M., and Snoeijs, P. 2007. A biological consequence of reducing Arctic ice cover: arrival of the Pacific diatom Neodenticula seminae in the North Atlantic for the first time in 800 000 years. Global Change Biology 13: 1910–1921. doi: 10.1111/j.1365-2486.2007.01413.x.

Reygondeau, G. and Beaugrand, G. 2011. Future climate-driven shifts in distribution of *Calanus finmarchicus*. Global Change Biology, 17, 756-766. 10.1111/j.1365-2486.2010.02310.x

Richardson, A., and Schoeman, D.S. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. Science 305: 1609–1612. Available from http://www.sciencemag.org/content/305/5690/1609.short.

Richardson, A.J. 2008. In hot water: zooplankton and climate change. Ices Journal of Marine Science, 65, 279-295. 10.1093/icesjms/fsn028

Riebesell, U. 2004. Effects of CO_2 Enrichment on Marine Phytoplankton. Journal of Oceanography 60: 719–728. doi: 10.1007/s10872-004-5764-z.

Riebesell, U., Zondervan, I., Rost, B., Tortell, P.D., Zeebe, R.E., and Morel, F.M.M. 2000. Reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature 407: 364–367.

Rykaczewski, R.R., and Dunne, J.P. 2011. A measured look at ocean chlorophyll trends. Nature 472: E5–E6.

Ryther, J.H. (1969) Photosynthesis and fish production in the Sea. Science, 166, 72-76.

Sameoto, D. 2001. Decadal changes in phytoplankton color index and selected calanoid copepods in continuous plankton recorder data from the Scotian Shelf. Canadian Journal of Fisheries and Aquatic Science 58: 749–761. doi: 10.1139/cjfas-58-4-749.

Sameoto, D. 2004. Northwest Atlantic plankton trends 1959 to 2000. Canadian Science Advisory Secretariat Research Document 2004/073.

Sarmiento, J.L., Slater, R., Barber, R., Bopp, L., Doney, S.C., Hirst, A.C., Kleypas, J., Matear, R., Mikolajewicz, U., Monfray, P., Soldatov, V., Spall, S.A., Stouffer, R.. 2004. Response of ocean ecosystems to climate warming. Global Biogeochemical Cycles 18: 6–7. doi: 10.1029/2003GB002134.

Schippers, P., Lurling, M., and Scheffer, M. 2004. Increase of atmospheric CO_2 promotes phytoplankton productivity. Ecology Letters 7: 446–451. doi: 10.1111/j.1461-0248.2004.00597.x.

Shackell, N.L., Frank, K.T., Fisher, J.A.D., Petrie, B. and Leggett, W.C. 2010. Decline in top predator body size and changing climate alter trophic structure in an oceanic ecosystem. Proceedings of the Royal Society B-Biological Sciences, 277, 1353-1360. 10.1098/rspb.2009.1020

Sherman, K., Reilly, J.O., Belkin, I.M., Melrose, C., and Friedland, K.D. 2011. The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems. ICES Journal of Marine Science. doi: 10.1093/icesjms/fsq177.

Silvert, W. and Platt, T. 1978. Energy flux in pelagic ecosystems - time-dependent equation. Limnology and Oceanography, 23, 813-816.

Smith, H.E.K., Tyrrell, T., Charalampopoulou, A., Dumousseaud, C., Legge, O.J., Birchenough, S., Pettit, L.R., Garley, R., Hartman, S.E., Hartman, M.C., Sagoo, N., Daniels, C.J., Achterberg, E.P., and Hydes, D.J. 2012. Predominance of heavily calcified coccolithophores at low CaCO3 saturation during winter in the Bay of Biscay. Proceedings of the National Academy of Sciences of the United States of America 109: 8845–8849.

Song, H., Ji, R., Stock, C., and Wang, Z. 2010. Phenology of phytoplankton blooms in the Nova Scotian Shelf-Gulf of Maine region: remote sensing and modeling analysis. Journal of Plankton Research 32: 1485–1499. doi: 10.1093/plankt/fbq086.

Song, H., Ji, R., Stock, C., Kearney, K., and Wang, Z. 2011. Interannual variability in phytoplankton blooms and plankton productivity over the Nova Scotian Shelf and in the Gulf of Maine. Marine Ecology Progress Series 426: 105–118. doi: 10.3354/meps09002.

Starr, M., Harvey, M., Galbraith, P.S., Gilbert, D., Chabot, D., and Terriault, J.-C. 2002. Recent intrusion of Labrador Shelf waters into the Gulf of St Lawrence and its influence on the plankton community and higher trophic levels. ICES CM Documents 2002/N:16.

Taucher, J., and Oschlies, A. 2011. Can we predict the direction of marine primary production change under global warming? Geophysical Research Letters 38. doi: 10.1029/2010GL045934.

Tortell, P.D., DiTullio, G.R., Sigman, D.M., Morel, F.M.M. 2002. CO_2 effects on taxonomic composition and nutrient utilization in an Equatorial Pacific phytoplankton assemblage. Marine Ecology Progress Series 236: 37-43.

Tremblay, M.J. and Roff, J.C. 1983. Community gradients in the Scotian Shelf zooplankton. Canadian Journal of Fisheries and Aquatic Sciences, 40, 598-611.

Ware, D.M. and Thomson, R.E. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the northeast Pacific. Science, 308, 1280-1284. 10.1126/science.1109049

Yamamoto-Kawai, M., McLaughlin, F.A., Carmack, E.C., Nishino, S., and Shimada, K. 2009. Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt. Science 326: 1098–1100. doi: 10.1126/science.1174190.

Chapter 4 A review of the physiological susceptibility of commercial species of fish and crustaceans of the northwest Atlantic to changes in water temperature, dissolved oxygen, pH and salinity

D. Chabot*[1], S. Guénette[2], and C. Stortini[2]

[1] Institut Maurice-Lamontagne, Fisheries and Oceans Canada, P.O. Box 1000, Mont-Joli, QC, G5H 3Z4

[2] Bedford Institute of Oceanography, Fisheries and Oceans Canada, P.O. Box 1006, Dartmouth, NS, B2Y 4A2

*Correspondence: Denis.Chabot@dfo-mpo.gc.ca

Suggested Citation:

Chabot, D., S. Guénette, and C. Stortini. 2013. A review of the physiological susceptibility of commercial species of fish and crustaceans of the northwest Atlantic to changes in water temperature, dissolved oxygen, pH and salinity. Ch. 4 (p. 83-168) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

4.1 INTRODUCTION

Climate change (CC) is expected to affect marine ecosystems through a suite of physical changes in the properties of water masses, such as sea level, temperature, acidification, salinity, oxygen, upwelling, stratification and the subsequent decrease in nutrient input from deeper waters, storm intensity and frequency, and changes in coastal run-off. These factors can directly impact the physiology of marine species, which can result in changes in growth rate and reproduction, as well as distribution changes (through emigration or differential survival). Changes in physical properties of water can also effect indirect changes on marine species, via changes in trophic webs (i.e., changes in productivity and distribution of prey species or changes in the timing of their availability to predators). Together, these changes produce changes in community species composition and biodiversity.

The aim of this chapter is to assess the possible impacts of climate change on exploited marine species of the Atlantic Large Aquatic Basin (LAB) and its sub-basins (Scotian-Shelf/slope and Gulf of Maine [SS-GM], Gulf of St. Lawrence [GSL] and Newfoundland and Labrador Shelf/Slope [NLSS]), using literature reviews, sometimes complemented by expert opinion. Only direct impacts are considered: the effects of temperature, dissolved oxygen, salinity and pH on physiology, productivity and survival, as reviewed in Chabot and Guénette (2013). However, the timing of larval emergence relative to prey availability is also mentioned. Indirect impacts on species, communities, and ecosystems, such as those resulting from changes in prey or predator abundance, or the timing of their abundance, changes in parasites and diseases, and differential survival and migration of species, are reviewed by Benoît and MacKinnon (Benoît and MacKinnon, 2013).

Nine commercial fish species are discussed first, in alphabetical order: American plaice, Atlantic cod, Atlantic halibut, Atlantic herring, Atlantic mackerel, capelin, Greenland halibut, haddock and redfish. Three crustacean species are then covered: American lobster, Northern shrimp and snow crab.

[Glossary (see Chabot and Guénette, 2013 for explanations): T_{cII} and T_{cI}: upper and lower critical (i.e., lethal) temperatures; T_{pII} and T_{pI}: upper and lower pejus temperatures; T_{opt}: optimal temperature for aerobic scope; T_{optG}: optimal temperature for growth; T_{optF}: optimal temperature for feeding; T_{pref}: thermal preferendum; SMR: standard metabolic rate; O_{2crit}: critical oxygen level, below which the fish cannot sustain its SMR; MMR: maximum metabolic rate (often called active metabolic rate, AMR, in fish); AS: aerobic scope, which is MMR – SMR]

4.2 DEMERSAL FISHES

4.2.1 American Plaice

4.2.1.1 Background

The American plaice, *Hippoglossoides platessoides*, is an arctic-boreal species of flatfish found on both sides of the North Atlantic. In the Western Atlantic, it is found from Baffin Bay and Davis Strait through the Gulf of Maine [GM] and Rhode Island, including all but the deepest part of the Atlantic LAB (Scott and Scott, 1988; Johnson et al., 1999; Busby et al., 2007). It is considered an eurybathic species. It can be found at depths from about 20 to 700 m, but usually occurs at depths of 70–275 m (Scott and Scott, 1988; Bowering and Brodie, 1991). It prefers sand (fine to coarse) but can be found on other bottom types as well (Morgan, 2000; Busby et al., 2007). American plaice performs limited migrations to deeper waters in winter (180–460 m in the GSL), and shallower waters in spring (40–150 m in the GSL) (Powles, 1965; Scott and Scott, 1988;

Swain and Morin, 1997; Swain et al., 1998). However eggs can drift considerably near the surface, allowing some mixing between stocks (Scott and Scott, 1988). Fisheries usually catch fish aged 6 to 20 y (~25–60 cm) (Powles, 1965; Scott and Scott, 1988). American plaice is an important commercial species in the Atlantic LAB, ranking 6th in landings and 7th in value among demersal fish[5], despite the fact that all stocks have experienced a strong decline (~86 to 95%) since the 1970s-80s (Busby et al., 2007).

4.2.1.2 Temperature

American plaice is considered a cold-water species. In the Atlantic LAB, it is most abundant at temperatures within -1 to 5 °C, although it occurs from -1.3 to 13 °C (Bigelow and Schroeder, 1953; Powles, 1965; MacKinnon, 1973; Scott and Scott, 1988; Bowering and Brodie, 1991). It generally avoids waters colder than -1.2 °C (Morgan and Brodie, 1991). Because of the seasonal migrations, American plaice are exposed to colder temperatures (shallower water) in spring and summer than in autumn and winter. In the southern GSL, for example, Powles (1965) observed that most fish were found between -1 and 4 °C in spring and summer, and between 2 and 5 °C in autumn and winter. Similarly, Swain (1998) found that American plaice were mostly distributed within -0.1 and 0.3 °C in late summer, but between 5.2 and 5.4 °C in winter. Field temperatures match closely those of laboratory experiments: American plaice can survive several weeks in water as cold as -1.4 °C, although they stop eating and lose weight. They can acclimate to temperatures as high as 17 °C (Morgan, 1992, duration not specified).

A slow growth rate, late maturation and spring-summer spawning characterize the American plaice in the northern part of its distribution, including the entire Atlantic LAB. On the contrary, in the southern part of its distribution (GM and Georges Bank), the American plaice has a fast growth rate, matures early and spawns in winter-spring (Walsh, 1994; Busby et al., 2007). In agreement with this general statement, growth rate increases with temperature within the species range in the West Atlantic: development is fastest in Passamaquoddy Bay and the Cape Cod region (bottom temperature of 10 °C, maturity reached at 3-5 years), and slowest off Newfoundland (Bay of Islands, 0 °C, 10–13 years) (Johnson et al., 1999).

As long as food is not limiting, fish would maximize growth rate by selecting the warmest bottom temperatures available. Instead, at least in the Atlantic LAB, they select cold temperatures relative to those available, especially the males. In the southern GSL, for instance, the temperature range within which 95% of the plaice were found was approximately -0.35 to 6 °C in males and -0.35 to 8 °C in females (Swain, 1997). Average temperature was approximately 1 and 1.5 °C in males and females, whereas average available temperature was ~2.5 °C. Median temperatures were lower (0.4, 0.55 and 0.8 °C for males, females, and available, respectively). Further, males tended to select colder temperatures at higher population size (Swain, 1997).

---

[5] In this document, fisheries statistics are for 2011, see <www.dfo-mpo.gc.ca/stats/commercial/land-debarq/sea-maritimes/s2011aq-eng.htm> and <www.dfo-mpo.gc.ca/stats/commercial/land-debarq/sea-maritimes/s2011av-eng.htm>.

Swain (1997) proposed that American plaice selected temperature so as to maximize energy gain as a function of food abundance, the behavioural energetics hypothesis reviewed in Chabot and Guénette (2013). The higher temperatures selected by females were assumed to be the result of greater fitness gains afforded by faster growth in females than males. A link between ration and preferred temperature has been demonstrated in the laboratory: well-fed American plaice preferred a temperature of 1.8 °C, on average, whereas plaice fed on a reduced ration preferred 1.2 °C (Morgan, 1993). However, this is a smaller drop in preferred temperature than required to validate the behavioural energetics hypothesis. There were other problems with some aspects of the behavioural energetics hypothesis. Furthermore, other studies found the behavioural energetics hypothesis unsatisfactory (see Chabot and Guénette, 2013). Sediment type could play a role in the selection of colder water by American plaice, especially if preferred sediments (fine to coarse sand) were correlated with colder temperature: sediment type strongly influenced habitat choice in the laboratory, even if the most favoured sediment was 1 °C colder than other sediments (Morgan, 2000). Predation by cod and Greenland halibut could also contribute to compress the thermal habitat of American plaice.

American plaice from the southernmost part of the distribution live in warmer water, the highest abundances being at 4–6 °C (Johnson et al., 1999), which also disagrees with the behavioural energetics hypothesis, unless the shelves are so much more productive (for plaice prey) in the GM and Georges Bank than in the Atlantic LAB, or unless plaice density is much less there, two hypotheses that were not addressed in this review.

Time of peak spawning is related to latitude, occurring later in the northern part of the distribution and earlier in the southern part. Thus peak spawning takes place in May or June off Labrador (Pitt, 1966), in April and May in the southern GSL (Powles, 1965) and on the Grand Banks (Pitt, 1966), and in March and April in the GM and Georges Bank (Bigelow and Schroeder, 1953; Howell and Caldwell, 1984). This latitudinal gradient is likely the result of the effect of bottom water temperature during autumn and winter on gonad maturation (Pitt, 1966; Walsh, 1994). In turn, spawning date determines the temperature regime experienced by the eggs and young larvae in the surface layer. This could lead to a mismatch between hatching and larval food supply in future years, because changes in bottom and surface temperatures are not expected to be synchronous (Chabot and Gilbert, 2013; Loder et al., 2013). However, the level of uncertainty is high in assessing the likelihood and impacts of a mismatch between fish larvae and their prey as a consequence of climate change (Benoît and MacKinnon, 2013).

Off Newfoundland and Labrador, spawning usually takes place between 1 and 3 °C (Pitt, 1966). The development rate of eggs and yolk-sac larvae is proportional to temperature within the 2 to 10 °C (from ~24 to ~7days, respectively) (Howell and Caldwell, 1984). The optimum temperature for eggs and early larvae appears to be between 2 and 6 °C because larvae are smaller at the resorption of the yolk sac at 10 °C. Large larvae are expected to feed more successfully and avoid predation better (Howell and Caldwell, 1984). The maximum temperature for successful development is between 10 and 14 °C as all embryos died at 14 °C (Howell and Caldwell, 1984). Eggs and larvae are mostly found between 50 and 90 m in the GM and Georges Bank (Johnson et al., 1999), where temperature is lower than in the first 10 m.

Optimum temperature for spawning is 3–6 °C and most of the spawning takes place at the 100 m isobaths, in the western GM and over southeastern Georges Bank (Johnson et al., 1999). Eggs have been collected at water temperatures of 1 to 12 °C, but mostly within 2–6 °C from February to March, and 5–8 °C from May to July. Eggs are mostly found at depths of 59 to 90 m (Johnson et al., 1999). Larvae have been collected at temperatures of 4–14 °C, but mostly at 6–8 °C. Juvenile and adult plaice are most abundant at 4–6 °C in spring and 6–11 °C in autumn (Johnson et al., 1999), a much higher temperature than that occupied by plaice in the GSL (see above).

4.2.1.3 Dissolved oxygen

Hypoxia tolerance is unknown for this species. This gap in knowledge is important considering the present use of deep, warmer and hypoxic water in winter, when adult American plaice tend to migrate below the cold layer they inhabit in summer (Busby et al., 2007). A possible loss of swimming capacity when American plaice are in the hypoxic zone could make them more vulnerable to fishing gear in autumn and winter. The risk will be higher in the GSL because of the more severe hypoxia in deep water there, at present and in the future.

4.2.1.4 pH

There is no information about the effect of pH on American plaice.

4.2.1.5 Salinity

American plaice are typically exposed to salinities of 32–34 (Munro et al., 1994), but can be found in waters with salinities down to 20-22 (Scott and Scott, 1988). In the laboratory, they have been found fairly tolerant to salinities down to 14 (Munro et al., 1994). Even at a salinity of 7, no mortality was observed over 96 hours, but several indicators of stress were elevated.

4.2.1.6 Conclusions

Salinity and depth do not appear to restrict the distribution of American plaice. There is no information about their tolerance to low levels of dissolved oxygen. This species is found within a narrow temperature range in the Atlantic LAB, but the fact that they occupy warmer temperatures in the GM and Georges Bank, where their growth rates are in fact better than in the Atlantic LAB, indicates that a warming in the Atlantic LAB might be less harmful than the present temperature distribution indicates. This would require an adequate food supply to fuel the faster metabolic rate resulting from an increase in temperature. Warming of the surface layer is more alarming, as the optimal temperature for eggs and larvae is around 4–6 °C, and the lethal temperature appears to be around 14 °C.

However, except for newly hatched eggs, which are found close to the surface, older eggs and larvae are found at depths where temperature should not exceed 14 °C even in 50–60 years. Further, as spawning takes place sooner at lower latitudes, it should also occur sooner after climate warming, allowing more time for larvae to metamorphose (3–4 months, Bigelow and Schroeder, 1953) and reach the bottom before the surface layer warms past 14 °C. There is however a risk of mismatch between larvae and their prey.

4.2.1.7 Synopsis for 2020-2030

In the southernmost part of the distribution (south of the Atlantic LAB), projected increases in variability of SST could result in more frequent years with temperatures greater than 6 °C, when the size of larvae at yolk-sac resorption is small, which is thought to be associated with reduced likelihood of feeding success and survival to predation. In the Atlantic LAB, such warm years would be favourable, as SSTs are presently lower than the optimal temperature for eggs and young larvae. The increased variability in bottom temperature is unlikely to be problematic for juveniles and adults, temperatures in the Atlantic LAB being so much colder at present than temperatures in the GM and Georges Bank, where these fish experience faster growth rate than in the Atlantic LAB, at least if the food supply is adequate. Considering the depleted status of most stocks at present, the food supply is likely to remain adequate.

4.2.1.8 Synopsis for 2060-2070

In the southernmost part of the distribution (south of the Atlantic LAB), the projected increase in stratification should keep the larvae within an acceptable temperature range despite the projected warming of SST, since the eggs and larvae are mostly found at 50–90 m. But if temperature reaches 10 °C at 50–90 m before June–July (expected time of metamorphosis), there could be decrease in recruitment. There is also a risk of mismatch between larvae and their prey because spawning time, which is controlled by bottom temperature, may not change at the same rate as planktonic blooms, which are controlled by SST (Chabot and Gilbert, 2013; Loder et al., 2013).

Projected warming of bottom temperatures is likely to reduce available habitat south of the Atlantic LAB. Increased hypoxia on the continental slope, where American plaice from the GM and Georges Bank spend the winter, may be a problem, but there is no knowledge of the hypoxia tolerance in this species. Despite the narrow temperature range used by this species in the Atlantic LAB, the projected warming of bottom water should not be deleterious except in the southern part of the range, or could even be advantageous, considering the high growth rates observed in the GM and Georges Bank during the last few decades. However, such benefits of warmer water will require an adequate food supply, otherwise growth rates will suffer instead of increasing. Wintering in the deep channels of the GSL and off southern Newfoundland and eastern Nova Scotia may result in reduced winter survival or fecundity due to projected worsening of hypoxia in deep water, unless hypoxia tolerance is high, or unless plaice migrate into shallower water as a result of the projected warming and reduced thickness of the CIL. Widespread dispersal due to the pelagic nature of eggs and larvae increases this species' ability to adapt or move away from unfavourably warm areas. No range extension is expected within the Atlantic LAB, which is already entirely occupied, but productivity could improve. The depleted state of the populations in the Atlantic LAB makes this species more vulnerable to warming than its temperature tolerance alone suggests.

4.2.2 Atlantic Cod

4.2.2.1 Background

The Atlantic cod (*Gadus morhua*) is found on both sides of the Atlantic from the GM to southern Labrador and Greenland in the western Atlantic, off Iceland, Scotland, and in the eastern Atlantic, from the Celtic Sea to the Barents Sea (Lilly et al., 2008). All stocks have been subjected to overfishing and shown signs of depletion (Lilly et al., 2008), and only a few of them have recovered (e.g., Northeast Arctic cod, ICES, 2011). Cod from the east coast of Canada have not yet recovered after the 1992 collapse in spite of fisheries moratoria (Bundy et al., 2009b). Despite the depleted status of most stocks, cod still ranks 3rd in landings and 4th in value among demersal fish in the Atlantic LAB.

Atlantic cod is one of the most studied species of marine fish in terms of physiology and responses to changing environmental variables. It is therefore reviewed in detail as an example of a species for which predictions are based on a good understanding of the processes involved.

4.2.2.2 Temperature

Because of its extensive geographic range, cod is distributed over a wide range of temperatures. Except for larvae, temperature near the bottom is the important parameter for this demersal fish, and the yearly average bottom temperature ranges from 2 to 11 °C for 17 cod stocks from the north Atlantic (Brander, 1994). Within this range, weight at age 4 increases linearly with average bottom temperature, each increase of 1 °C resulting in a 29% increase in growth rate (Brander, 1994). Interestingly, 8 of these 11 stocks are within the Atlantic LAB. Five are cold water stocks (2–2.5 °C: Labrador/Grand Bank [NAFO divisions 2J3KL], Southern Grand Bank [3NO], northern GSL [3Pn4RS], southern GSL [4T] and St. Pierre Bank [3Ps]), the remaining three can be considered as intermediate-temperature stocks (5 °C, eastern Scotian Shelf [SS], 6 °C, western SS, and 8 °C, Georges Bank). Stock comparisons also reveal that condition (i.e., energy reserves) is positively correlated with mean bottom temperature (Rätz and Lloret, 2003) and that condition and fecundity are reduced at higher latitudes (Pörtner et al., 2001). Similarly, interannual temperature variations influence growth rate and condition within populations (Drinkwater, 2005; Lambert, 2011). Brander (1994) concludes that changes in growth rate are a major, predictable effect of climate change for this species.

Laboratory studies with unlimited food supply confirm that generally speaking, cod growth rate increases with temperature, but when this is studied in greater detail, age-related differences become apparent, as well as the fact that there is an optimal temperature (T_{optG}). Past this optimum, growth rate declines (Björnsson et al., 2001; Björnsson and Steinarsson, 2002; Björnsson et al., 2007). T_{optG} is highest for the smallest fish (15 °C at 2 g, and declines progressively in larger cod (14, 12, 10.5, 10, 9 and 8.5 °C at 10, 100, 500, 1000, 2000 and 5000 g, respectively) (Björnsson et al., 2007). Temperatures that favour growth rate also result in good condition indices. For each size class, the relationship between growth rate and temperature is dome shaped, so that gains (in growth rate) slow down near T_{optG}. As a result, stocks in relatively warmer water, such as SS-GM, are expected to benefit less from warming temperature because of a reduced increment in growth per degree increase in temperature (Brander, 2010).

Genetic differences among stocks could reduce the benefits of warming. Cold-adapted stocks can have an elevated metabolic rate to increase performance at low temperature, and this elevates their maintenance requirements and reduces their performance at high temperature (Pörtner et al., 2001). However, results are conflicting for cod. Pörtner et al. (2001) report slower growth rate at intermediate and high temperatures for cod from cold-water stocks than for warm or intermediate-water stocks, a demonstration of genetic adaptation. Conversely, cod from southern GSL grow just as well at 7–13 °C as cod from the Bay of Fundy (SS-GM) (Dutil et al., 2008), despite the fact that the former is a cold-water stock (2.5 °C, Brander, 1994) and the latter is a mild-temperature stock (6 °C, Brander, 1994). Brander (2010) considers genetic differences in growth rate of cod to be small and under similar feeding conditions, temperature and light level seem to be the main factors explaining growth differences between populations.

Overall, comparisons of different stocks and results from laboratory experiments suggest that the warming trend of deep water in 10–20 and larger predicted increases in 50–60 years should result in faster growing cod in the Atlantic LAB. However, this could be compromised by indirect effects, especially for the SS-GM stock, which will benefit from smaller increases in growth rate (because it is close to T_{optG} at present, see above). Indirect negative effects could come from shifts in the abundance or distribution of important prey species. Changes in energy density or lipid composition of prey could alter both growth rate and gonad maturation (spawning date), and therefore influence survival rate of larvae (Røjbek et al., 2012).

When given the choice, smaller cod favoured warmer temperatures than larger cod (6.9 °C at 2 g and 3 °C at 4700 g, Lafrance et al., 2005) in laboratory determinations of T_{pref}. Stock differences also appear likely, as juvenile cod (~130 g) from the Kattegat (Denmark) had a warm thermal preferendum (13.9 °C, Schurmann and Steffensen, 1992), compared with cod from the northern GSL (6.5 °C at 1.2 kg, Despatie et al., 2001). The northern GSL fish were larger (~940 g) but the difference in thermal preferendum was too large to be caused by size alone. Despatie et al. (2001) found that cod on a low ration sought colder water than cod that were fed ad libitum, which was interpreted as an energy saving measure, since this slowed metabolic rate. This supported Swain and Kramer's

(1995) hypothesis that southern GSL cod selected colder temperatures when abundance was high as an energy-saving measure. There may be population differences in thermal preferendum, but the thermal preferendum of cod does not match T_{optG} and it is not clear if this concept can be used to estimate the impact of CC on the future distribution or growth rate of cod.

Critical temperature thresholds depend on acclimation temperature. Thus the upper lethal threshold for 5 °C acclimated cod is 16.5 °C, but it becomes 21.5 °C for 16 °C acclimated cod (Jobling, 1988 and references therein), although no details are provided to assess surviving time at such high temperatures. In more recent studies, the upper critical temperature was around 19–24 °C in Newfoundland cod acclimated at 10 °C (Gollock et al., 2006; Pérez-Casanova et al., 2008) and North Sea cod acclimated at 10–12 °C acclimated (Sartoris et al., 2003). The physiological mechanism that becomes limiting for oxygen delivery to tissues is debated for this species, some arguing that the heart fails because venous blood, which supplies oxygen to the heart, becomes too depleted in oxygen (Sartoris et al., 2003), where others found no such limitation in cardiac function, but observed a decline in the oxygen binding capacity of blood (Gollock et al., 2006). Pérez-Casanova et al. (2008) observed elevated values for stress indicators above 16 °C suggesting, that T_{cII} was around 16 °C. Although less relevant in the context of climate warming, the cold critical temperature is about -1 to 0 °C (Jobling, 1988), and even colder for juveniles that produce plasma antifreeze proteins (Hew et al., 1981; Fletcher et al., 1987; Goddard et al., 1994).

As reviewed in Chabot and Guénette (2013), it has been proposed that temperatures for long-term survival (weeks or longer) and thus species distribution lie within the two pejus temperatures (T_{pI} and T_{pII}) instead of the two critical temperatures (T_{cI} and T_{cII}). Sartoris et al. (2003) suggested that T_{pII} is 13 to 16 °C in cod. Lannig et al. (2004) lowered T_{pII} to ~7 °C, with a slow drop in performance between 7 °C and 16 °C, the later being T_{cII}. However, as stated earlier, T_{cII} was higher than 16 °C in other studies (Gollock et al., 2006; Pérez-Casanova et al., 2008). Differences in T_{cII} are in part the result of differences in procedures, in particular the choice of acclimation temperature and, for experiments based on survival, the duration of the experiment. Taken together, these results suggest that the upper limit of average bottom temperature for cod stocks and also T_{pII} is between 10 and 14 °C, which agrees well with Brander (1994).

Warming and cooling trends can cause distribution changes at the northern and southern limits of a species' distribution, as local temperature falls out of range of T_p. Past warming and cooling events have resulted in changes in the distribution of cod (for a review, see Drinkwater, 2005). Projected increases in bottom temperature suggest that the Atlantic LAB will not become too warm for cod, except possibly the GM part of SS-GM. The extent of the cod distribution is already up to the northerly limit of the Atlantic LAB, so any future range extension as a result of climate change would take place outside of the Atlantic LAB.

Egg development and hatching success, as well as larval survival and growth rate, are influenced by Sea Surface Temperature (SST). T_{optG} is > 12 °C for cod eggs (Wieland et al., 1994) and 15 °C for larvae (Otterlei et al., 1999) and 2 g juvenile fish (Björnsson et al., 2007). Optimal temperature for feeding is 12 °C for 0.9 g juvenile cod, and 8 °C for 7.3 g cod (Peck et al., 2003). The relationship between recruitment and SST is positive for cold-water stocks, non-existent for temperate-water stocks, and negative for warm-water stocks (Planque and Frédou, 1999; Lehodey et al., 2006; Mantzouni and MacKenzie, 2010). Because recruitment seems to be optimal when SST during the summer is around 8 °C, even though growth and food intake continue to improve with further warming, there must be indirect effects of warming that reduce recruitment above 8 °C, as in North Sea cod (O'Brien et al., 2000). One possible factor is survival rate. Spawning date is influenced by bottom temperature, food availability and density-dependent processes during gonad development (Wieland et al., 2000), and is thus mostly under the influence of conditions experienced by adults in deep water. Larvae survival and growth rate are related to SST, but also to the availability of prey, itself influenced by SST. Despite large differences in mean bottom temperature among cod stocks, and seasonal differences in bottom temperature within stocks, Mantzouni and MacKenzie (2010) found that recruitment decreased when spawning occurred at temperatures > ~6.5–7 °C, and that temperature differences between stocks were smallest around spawning time, which suggests that cod evolved to spawn at a temperature which correlated with greater survival of eggs and larvae. Changes in temperature are projected to be more pronounced, and likely to occur earlier in the surface layer than in deep water, which could negatively impact the relationship between spawning temperature and recruitment.

Drinkwater (2005) has tried to simplify the problem and estimate the combined impacts of climate change on cod abundance (i.e., on growth rate, condition of adults, and recruitment). The main element of this simplification is to assume that temperature will change at the same rate through the water column. For instance an increase of 2 °C in the annual mean SST would be accompanied by a 2 °C increase in the annual mean bottom temperature, at least for the waters where most cod stock are found (50–400m). Thus the possibility that different rates of warming according to depth will result in a possible mismatch between cod larvae and their prey is ignored. Keeping this in mind, Drinkwater's analysis is the only one we know that calculated a change in recruitment per degree change in SST, as a function of bottom temperature (present or future). Predictions of warming by 2–4 °C (annual average) by year 2100 were considered. On this basis, the productivity of southern stocks is predicted to decline as temperature increases while productivity of northern stocks would increase. For the Atlantic LAB, a sustained 1 °C increase would result in a decrease in production of the Georges Bank stock, no change for the GM and western SS stocks, but an increase for the other stocks. The results of a 2 °C increase would be similar, except that the Flemish Cap stock may level off. A sustained 3 °C increase is predicted to result in a decline in productivity for southern stocks (Georges Bank, GM, Browns Bank-Bay of Fundy, essentially the SS-GM area of the Atlantic LAB) and continued increases in the productivity of the other Atlantic LAB cod stocks, except for the southern Grand Bank and the Flemish Cap stocks. With the most extreme climate change scenario (+4 °C) examined by Drinkwater (2005), the Georges Bank stock is likely to disappear, the SS-GM as well as the Flemish Cap stocks would decline, most other stocks would remain stable, with only stocks from the southern GSL, southern Labrador and northeast Newfoundland would increase.

4.2.2.3 Dissolved oxygen

There are many areas of the world where cod has to contend with low levels of dissolved oxygen (DO) or hypoxia at the present, such as the Baltic Sea (Tomkiewicz et al., 1998; Neuenfeldt, 2002; Neuenfeldt and Beyer, 2003; Chabot and Gilbert, 2008), the Kattegat (Pihl, 1994), and the Estuary and northern GSL (D'Amours, 1993). Down to ~70% saturation (sat.), DO level has little impact on cod except for a small decrease in AS and thus maximum performance (Dutil et al., 2007). Within the range 30–70% sat., growth rate is proportional to DO level, owing to reduced food consumption (Chabot and Dutil, 1999). The link between food consumption and DO level involves a reduction in amplitude of the peak of oxygen consumption that accompanies digestion, which is compensated by an increase in duration of postprandial oxygen consumption (Jordan and Steffensen, 2007). This is thought to reduce throughput of food (Chabot and Claireaux, 2008). This limitation in postprandial oxygen consumption is the result of the reduced AS imposed by hypoxia on fish (Fry, 1971). At 50% and 30% sat., only ~50% and ~30% of the AS observed in normoxia remains, respectively (Claireaux et al., 2000; Chabot and Claireaux, 2008). Plante et al. (1998) began to observe mortality at 28% sat. in the laboratory, which is well matched by research surveys: practically no cod is caught in parts of the Estuary and Gulf with less than 30% sat. (D'Amours, 1993), and cod density is directly related to DO in the 30–70% sat. range (Chabot, 2004). Finally, the lethal DO threshold is ~15–21% sat. for juvenile and adult cod within the range 2–10 °C (Schurmann and Steffensen, 1997; Plante et al., 1998; Claireaux et al., 2000). Areas where DO close to the bottom is < 30% sat. constitute lost habitat for cod. Cod can make short (a few hours to a few days, depending on the exact DO level) incursions into such waters (Claireaux et al., 1995; Neuenfeldt et al., 2009), but cannot reside there.

Deep-water hypoxia in the EGSL is expected to become more severe in 10, and mostly 50 years, although the extent of the drop in oxygen is impossible to predict (Chabot and Gilbert, 2013). This drop in DO will be accompanied by an increase in bottom water temperature (Chabot and Gilbert, 2013), and thus a reduction in oxygen solubility and an increase in metabolic rate of fish. Increased temperature and metabolic rate decrease hypoxia tolerance in fish, including cod (Claireaux et al., 2000). Considering that hypoxia already exclude cod from the Laurentian Channel in the Estuary, and the head of the Anticosti and Esquiman Channels, and that an important proportion of the northern GSL cod stock is found in waters where growth rate is limited by DO (Chabot, 2004), the predicted changes in bottom DO and temperature are likely to restrict this stock to the shallower shelves (< 175 m) and coastal waters.

4.2.2.4 pH

Cod seem impervious to pH changes within the range of predicted values up to year 2100 and beyond. Cod eggs were incubated at different pH until larvae hatched and reached first feeding stage, and there was no impact of pH on any of the variables measured (Frommel et al., 2012). The pH levels tested were 7.97, 7.83, 7.75, 7.68, 7.61 and 7.21, corresponding to PCO_2 values of 380 µatm (current global sea surface concentration), 560, 860 (level predicted in 2100), 1120 and 4000 µatm. The variables investigated were hatching success, survival, development and otolith size. Older cod are also tolerant of low pH values expected under high atmospheric CO_2 conditions. Juvenile cod (~12 g) reared for 63 days at elevated PCO_2 (12 mg l^{-1}) and pH down to 7.5 had the same final weight as the control group. However, specific growth rate was lower at the lowest pH during the last phase of the rearing period (Foss et al., 2006). That study did not control pH, however, and PCO_2 and pH varied in time for each treatment, and generally speaking, low pH was accompanied by low DO and high ammonia concentration. When pH is directly controlled by CO_2 manipulation, acidic water has no impact, even for long-term exposition (4 and 12 months) of juvenile cod (~220 g) at PCO_2 of 3080 µatm (pH 7.3) and 5792 µatm (pH 7.01): swimming performance was the same as control cod, indicating that AS was not reduced at low pH and presumably that there was no disturbance to acid-base balance (Melzner et al., 2009). However, another study with a shorter exposure found a reduction in growth rate of juvenile cod (Moran and Stottrup, 2011). The fish (20–80 g) were exposed to 3 CO_2 levels for 55 days: low (1000 µatm, pH = 7.9), medium (3800 µatm, pH = 7.4) and high (8500 µatm, pH = 7.06). Growth was reduced at pH of 7.4 and 7.06. More work is required to explain these opposing results. It should be noted that the pH levels that reduced growth in the laboratory are not expected to occur during this century.

Acidification is most severe in zones that are hypoxic (Melzner et al., 2012). Studies of the effects of hypoxia on cod physiology have taken place in seawater with normal pH. It is possible that low pH acts synergistically with hypoxia. This is a major shortcoming in our understanding of hypoxia tolerance in cod.

4.2.2.5 Salinity

Cod is considered an extremely euryhaline species. Normal egg development requires a salinity of 11 (Westin and Nissling, 1991). In juvenile and adult cod, growth rate is actually faster at intermediate salinity levels (13.5–15) than at 28–32 (Lambert et al., 1994; Árnason et al., 2013), with no negative effect (stress or immune responses) (Árnason et al., 2013). Salinity influences the buoyancy of cod eggs and in the Baltic Sea, eggs sometimes sink into the severely hypoxic zone and die because of low surface salinity (Nissling et al., 1994; Nissling and Westin, 1997). No direct effect of salinity changes is expected for cod in the Atlantic LAB. However, indirect effects remain possible. Small declines in salinity can indirectly influence cod recruitment (Myers et al., 1993), probably through direct effects on prey of larvae and juveniles.

4.2.2.6 Conclusions

The study of Drinkwater (2005) provides the best summary of the predicted impacts of a few climate change scenarios on cod populations. These scenarios are similar to the projections for the Atlantic LAB (Chabot and Gilbert, 2013; Loder et al., 2013). Cod stocks in SS-GM will remain stable, but will decline if the increase in annual mean bottom temperature reaches 4 °C. The other stocks will see productivity gains (growth, condition, recruitment) with climate change, with a few of these stocks becoming stable or declining with the more extreme scenario (4 °C increase in annual mean bottom water temperature). Drinkwater (2005) did not take hypoxia into account. A worsening of hypoxia in the deep channels of the GSL would reduce the production gains that he predicted for the northern GSL stock, or even cause production losses.

With the warming of SST and bottom water temperature predicted in 50 years, cod distribution is expected to extend further north than at present (Drinkwater, 2005), but these gains will take place outside of the Atlantic LAB. In parts of the Atlantic LAB characterized by a winter ice cover at present, the probable disappearance of ice or shortening of ice season may impact critical life-history traits, such as overwintering spawning migrations and residence on feeding grounds (Drinkwater, 2005). For stocks which are predicted to decline because of exceedingly warm temperature, the decline could be accelerated if fishing practices are not adapted to the reduced productivity (Drinkwater, 2005), just as fishing is thought to have exacerbated the negative impact of a very cold period in the northern GSL in the late 1980s and early 1990s (Lambert, 2011). Further, stocks that are depleted are less resilient to temperature changes because of their reduced age range (Brander, 2010). This is exemplified for northern cod, which collapsed in the early 1990s: the age and length structure were truncated and the catch was dominated by 3 age classes (4-6), compared with that of the 1960s that included cod of up to 20 years old (Lilly et al., 1999).

Predictions of increased growth rate for cold-water stocks benefiting from a warming of water by a few degrees assume that cod will find food to sustain the increased metabolic rate that accompanies warmer temperatures, either because its present prey react similarly to increased temperature, or because new prey would become available. But this may not be the case. Warming is known to favour copepod species in the North Sea that are not in phase with that of larval cod, causing a mismatch between cod larvae and its food supply, and reduced larvae survival (Beaugrand et al., 2003). Such a replacement of favourite copepod food species by less profitable species is more likely at the southern edge of the cod distribution (Beaugrand and Kirby, 2010), such as the SS-GM. Also, Drinkwater's (2005) predictions are based on a simultaneous warming of the entire water column, whereas SST increases are expected to occur sooner and be more pronounced than increases in bottom temperature, at least at depths that are below the CIL (Chabot and Gilbert, 2013; Loder et al., 2013). As stated previously, this could increase mismatch between larval emergence and food supply.

4.2.2.7 Synopsis for 2020-2030

Cod larvae should benefit from projected increased frequency of warm SST years, with better growth and survival, except in years where SST values at time of spawning are > 8 °C, which are associated with poor recruitment. Most southerly populations (SS-GM) might suffer from low recruitments during warmest springs, but this may be offset by increased juvenile survival.

Small projected changes in bottom temperature, in the Cold Intermediate Layer (CIL) core temperature and CIL thickness should have a minor but favourable impact on growth of juvenile and adult cod because all stocks are below the optimal temperature for growth. Changes in DO should be too small to have any impact on depleted populations in the GSL.

4.2.2.8 Synopsis for 2060-2070

Egg development will benefit from projected increases in bottom temperature and this should result in earlier spawning, but it remains to be seen if spawning will match the predicted earlier spring plankton bloom. If it does, cod larvae should benefit from projected increased SST in spring and summer, with better growth and survival. Very warm SSTs at time of spawning (> 8 °C) may result in low survival but this should affect only the SS-GM stocks.

Projected changes in bottom temperature, in CIL core temperature and CIL thickness should be favourable for growth of juvenile and adult cod because all stocks are presently several degrees below the T_{optG}. This is less true for SS-GM, where present conditions are closer to T_{optG}. This assumes that food will not be limiting (i.e., that cod prey will also fare well). Predicted decrease in DO below the CIL in areas influenced by slope water may decrease productivity because of the link between DO, food consumption and growth. Areas where DO is less than 30% saturation are inhospitable for cod, except for short forays. Cod may be excluded from the Laurentian Channel west of Anticosti Island and from the head of the Esquiman and Anticosti Channels. The loss of the deep habitat would reduce the carrying capacity of the northern GSL.

4.2.3 Atlantic Halibut

4.2.3.1 Background

The Atlantic halibut, *Hippoglossus hippoglossus* is the largest of flatfishes: it can reach over 300 kg, although specimens larger than 100 kg are rare nowadays (Cargnelli et al., 1999). It is found in the northern Atlantic and some parts of the Arctic Ocean (Cargnelli et al., 1999; Trzcinski et al., 2011). In the northwest Atlantic, it occupies a wide latitudinal range extending from the Labrador shelf to Virginia, but the area of highest abundance is along the southern edge of the Grand Bank and on the SS from Browns Bank to Banquereau Bank (Scott and Scott, 1988; Cargnelli et al., 1999). The western SS is probably a nursery area (Neilson et al., 1993). The Atlantic halibut is a highly mobile species (Bowering, 1986; Trzcinski et al., 2011).

The Atlantic halibut was heavily exploited off New England as early as the beginning of the 19th century, and that population was depleted by the end of the century (Trzcinski et al., 2011). In Canadian waters, landings have been recorded since the late part of the 19th century. They increased steadily until the middle of the 20th century, but declined afterward. Abundance has increased again in recent years (Trzcinski et al., 2011). In 2011, it ranked 8th in landings, but 2nd in value, among demersal fishes in Atlantic Canada. In addition, this species has received attention as an aquaculture species in Europe and Canada (Björnsson and Tryggvadóttir, 1996).

Atlantic halibut spawn in late winter and spring (Scott and Scott, 1988) in deep water (Neilson et al., 1993). The eggs are bathypelagic but development is thought to occur close to the bottom because of their negative buoyancy (Cargnelli et al., 1999). The larvae are found within the first 50 m of the water column. Juveniles are found in nurseries located on shelves, and older fish disperse. Females grow faster and reach larger sizes than males (see review in Cargnelli et al., 1999).

4.2.3.2 Temperature

According to several authors (Bowering, 1986; Cargnelli et al., 1999, and references therein), optimal temperatures for eggs are 4–7 °C in lab experiments, with development time inversely proportional to temperature (incubation time to 50% hatch is 20 days at 4.7 °C, 18 days at 5 °C, and 13 days at 7 °C). However it is not clear if warmer temperatures were tested and found suboptimal, or if the maximum temperature tested was 7 °C. There is no formal information on the temperature requirements of larvae, but they are known to develop normally at ~5 °C. The temperature requirements of juveniles are undefined, but they can survive sub-zero temperatures in winter, although they cease feeding below 2 °C. Juveniles are usually found at 20–60 m, (SST and CIL). Adults are found at ~40–1000 m. Many populations seem to migrate seasonally, occupying deeper waters in winter. The adult temperature range is -0.5–13.6 °C, although most catches take place between 3 and 9 °C, and average temperature of the catches is 5 to 6 °C. Scott and Scott (1988) mention that adults are rarely found below 2.5 °C.

In the laboratory, younger Atlantic halibut have a higher T_{optG} than larger fish (Björnsson and Tryggvadóttir, 1996): ~14 °C at 10–60 g, 11.4 °C at 100-500 g, and 9.7 °C at 3–5 kg. Optimal temperature for growth efficiency (GE, weight gain divided by weight of food eaten) is also higher in small fish, and a bit lower than T_{optG}. Temperature ranges that are optimal for growth and GE are 12–13 °C at 10–60 g, 8–11 °C at 100–500 g, and 6–9 °C at 3–5 kg. Thermal sensitivity close to the optimum decreases with fish size (Björnsson and Tryggvadóttir, 1996), meaning that a wider range of temperatures provides good growth rates in large more than in small fish.

4.2.3.3 Dissolved oxygen

According to the single study available, juvenile Atlantic halibut (~41 g) are very sensitive to hypoxia, with a significant reduction of growth rate at 84% sat., and a more pronounced slowing of growth at 53% sat. (Thorarensen et al., 2010, at

13 °C, salinity of 17.3 units). There are no data for older fish. Hypoxia tolerance is unknown, but Atlantic halibut are found in the St. Lawrence Estuary and the deep channels of the GSL at present (Bourdages and Ouellet, 2011). DO levels of 20–30% sat. are common in these waters (Gilbert et al., 2005; Gilbert et al., 2007; Chabot and Gilbert, 2013).

4.2.3.4 pH

There is no information on the possible impact of ocean acidification on Atlantic halibut. However, they are found in the deep channels of the GSL and in the St. Lawrence Estuary, where the waters are hypoxic and acidic (pH = 7.7) (Mucci et al., 2011; Chabot and Gilbert, 2013).

4.2.3.5 Salinity

According to Cargnelli et al. (1999), eggs and larvae are neutrally buoyant at salinities of 34.7–36.5. On SS, adults are found at salinities ranging from 30.4 to 35.3.

4.2.3.6 Conclusions

This species is distributed over a wide temperature range, especially juvenile fish. Because the temperatures presently found in the Atlantic LAB are below T_{optG} obtained in the laboratory, it appears that the Atlantic halibut is not particularly at risk due to the projected increases in temperature in the Atlantic LAB, except possibly in SS-GM.

4.2.3.7 Synopsis for 2020-2030

There are no studies investigating the impact of extreme weather events (and SST) on recruitment, so the impact of increased frequency of warm springs on recruitment is unknown. Juvenile and adult Atlantic halibut are highly mobile and have a wide temperature range. Extreme events and climate change will probably not change distribution in the short term and may increase productivity in the Atlantic LAB.

4.2.3.8 Synopsis for 2060-2070

The direct impact of projected changes in SST on recruitment is unknown, but there is a risk of phenology mismatch: adult halibut spawn at depths where temperatures are increasing less rapidly than at the surface, where eggs and larvae develop. Increased rate of gonadal development at depths with warming may not be rapid enough to match temperature conditions at the surface. Eggs could be released into surface waters that are too warm for survival or proper development, or that are less productive (projected earlier planktonic blooms). Larval development is expected to improve in the northern part of the Atlantic LAB (NLSS).

Juvenile and adult Atlantic halibut are highly mobile, insuring efficient dispersal, and have little habitat specificity. They are likely to shift distribution north, disappearing from the southern limits of its range (i.e., Cape Cod) with projected increases in bottom temperatures. Distribution may be expanded north of

Newfoundland/Labrador. Productivity is likely to increase in NLSS. No net change is expected on the SS-GM. For these reasons, this species is not sensitive and is very adaptable to, or can escape easily from, warming conditions. However, low resilience and commercial status may limit adaptability if other pressures intensify alongside accelerated warming. Atlantic halibut may experience a decrease in dissolved oxygen due to their deep habitats (25-1000 m). Hypoxia is expected to become more prevalent in waters below 175 m, along with a projected increase in temperature. This may restrict the vertical range to shallower waters, possibly decreasing abundance. If some fish remain in deeper waters, they could suffer decreased growth and reproductive capacity. Hypoxia will become very severe in the deep waters of the GSL and habitat loss may be more severe there. This species' tolerance to hypoxia is unknown.

4.2.4 Greenland Halibut

4.2.4.1 Background

Greenland halibut, *Reinhardtius hippoglossoides,* is a circumboreal cold stenothermic species found at depths of 90 to 1600 m (Scott and Scott, 1988), with larger fish usually occupying deeper waters (Ernst, 1987; Jørgensen, 1997; Bowering and Nedreaas, 2000). It is an important commercial species in its distribution range, being exploited in the northeast and northwest Atlantic (i.e., all but the southermost part of the Atlantic LAB) (Bowering and Nedreaas, 2000), the Canadian Arctic (Pike, 1994), and the northern Pacific (Alton et al., 1988). Unlike most other demersal species, Greenland halibut stocks did not collapse in the late 1980s and early 1990s in the Atlantic LAB (Dawe et al., 2012). In recent years, halibut landings have been the second highest among demersal fish in the Atlantic LAB, and the third fish species overall. It is the most valuable fishery of finfish in the Atlantic LAB. These fish show sexual dimorphism, males growing more slowly and reaching smaller maximum sizes (~70–80 cm) than females (up to > 100 cm) (Scott and Scott, 1988). Its main prey species in the Atlantic LAB are capelin, northern shrimp, Gonatus squid, Themisto amphipods, euphausiids and arctic cod (Bowering and Lilly, 1992; Orr and Bowering, 1997; Dawe et al., 1998; Dwyer et al., 2010; Bernier and Chabot, 2013).

4.2.4.2 Temperature

No laboratory study exists for the thermal tolerance of the Greenland halibut, nor for effect of temperature on its growth rate. Its temperature tolerance (T_{pI} and T_{pII}) must be inferred from its distribution. In the northwest Atlantic, the Greenland halibut is found as far south as the SS, but not in the GM according to Bigelow and Schroeder (1953). Eastern and Southern SS are characterized by an annual average bottom temperature of 5 and 6 °C (Brander, 1994). The neighbouring Georges Bank, where there is no Greenland halibut, has an average bottom temperature of 8 °C (Brander, 1994). This suggests that T_{pII} is approximately 7 °C. This agrees well with the occupied range described by Scott and Scott (1988), -0.5 to 6.0 °C.

Generally speaking, populations usually live within a temperature range of 4 °C. There are no reports of Greenland halibut stocks being abundant in waters warmer than 6 °C. Reviewing several studies and his own data for Davis Strait (divisions 3K and 2), Ernst (1987) concluded that larger fish are found at greater depths and within a narrower temperature range (3–4.4 °C) than smaller fish (-1.5–6 °C). It is not clear if the narrower temperature range represents active selection by the fish or is a direct consequence of the temperatures available at these deeper depths. In the Northwest Atlantic, Greenland halibut are most abundant at bottom temperatures mainly between 2 and 6 C° compared to 0 to 4 °C in the Northeast Atlantic (Bowering and Nedreaas, 2000). There are some differences among stocks from the Northwest Atlantic, however, with more northerly stocks using colder water (from < 0 to 5 °C, Davis Strait) than southerly stocks (from < 0 to > 7 °C, Flemish Cap and Grand Bank, but with very low catches below 3 °C and above 5 °C). In west Greenland, Greenland halibut are found in a very narrow temperature range, 1.2–3.5 °C, with spawning taking place in the warmer water (3–3.5 °C, > 1200 m) (Jørgensen, 1997). The GSL population is a warm-water population. Juveniles are most abundant at depths > 200 m and temperatures of 5–6 °C (Youcef et al., 2013). This entire population lives at ~200–350 m (Bourdages and Ouellet, 2011) and at 4.5–6 °C (Galbraith et al., 2013).

In Cumberland Sound, Baffin Island, eight Greenland halibut (> 80 cm, thus females) were equipped with pop-off tags. The modal temperature was 2.5 °C, the mean was 2.2 °C (SD: 0.01) and the entire temperature range was very narrow: 1.3 to 2.7 °C (Peklova et al., 2012). These fish occupied deeper (1047 ± 112 m, N = 7), slightly warmer (> 2.3 °C) waters from August to December. During the period of ice cover (January to May), average depth was 823 ± 123 m, N = 2) and average monthly temperature was 1.8 to 1.9 (Peklova et al., 2012).

A weak link between temperature and recruitment has been shown for Northeast Atlantic Greenland halibut: in scientific surveys, catch rates of 1-group (1 y-old) Greenland halibut declined when average bottom temperature during the first 2 years of life (age 0 and 1) was > 3 °C, and they were almost nil when bottom temperature was ≥ 4.5 °C (Albert et al., 2001).

4.2.4.3 Dissolved oxygen

Greenland halibut, especially juveniles, are frequently found in severely hypoxic areas (18–25% saturation) of the St. Lawrence Estuary (Youcef et al., 2013). In the laboratory, hypoxia tolerance, as measured by O_{2crit} at 5 °C, is 15% saturation in juveniles and 11% in adults, indicating that the juveniles are more sensitive to hypoxia than the adults (Dupont-Prinet et al., 2013b). Because hypoxia limits MMR, AS is reduced in hypoxia (Fry, 1971). Severe hypoxia (19% sat.) reduces AS of juvenile Greenland halibut by 72%. These young fish are nevertheless able to invest as much in postprandial metabolism as fish digesting in normoxia, although there was a small but significant increase in the duration of postprandial metabolism. This suggests that bolus transit time is on the verge of limiting feeding intensity. Considering that the estuary is a nursery for the GSL population (Youcef et al., 2013), Dupont-Prinet et al. (2013b) concluded that the growth and distribution of this population could be affected if there are further declines in DO in the deep water of the GSL.

4.2.4.4 pH

There are no data on the effect of pH on Greenland halibut physiology. However this species is abundant in the St. Lawrence Estuary, especially the juveniles (Youcef et al., 2013), and this severely hypoxic zone is characterized by low pH at the present (Mucci et al., 2011). There was a difference of ~0.1 in pH between surface and bottom waters in the 1930s (~8.08 vs ~7.98, respectively). Whereas the pH has not changed noticeably in the surface layer since then, it has fallen to ~7.7 in the deep layer (Mucci et al., 2011). There has been no observation of ill effect on Greenland halibut, but this has never been studied in detail, nor has there been any study of possible interactions between hypoxia and acidification.

4.2.4.5 Salinity

There is no study of the salinity tolerance of Greenland halibut. All populations live in deep ocean water with stable salinity. No major change in salinity is expected at these depths.

4.2.4.6 Conclusions

Although there is no study to describe the impact of temperature on Greenland halibut survival, growth and recruitment, distribution of Greenland halibut populations reveal that this is a cold stenothermic species, with very few occurrences at temperatures above 6 °C, and this temperature is likely close to TpII for the species. Two populations (SS, GSL) are already living at 4–6 °C. A warming of 1–2 °C might extirpate these populations, especially that such a warming would be accompanied by a lowering of DO, which is itself already close to limiting food consumption and growth in the main nursery of the GSL population. Parts of the NLSS (Flemish Cap, Grand Bank) which are already at ~6 °C may become too warm for Greenland halibut, but the fish could take refuge in the colder parts of the area. No positive aspect to climate change is expected for this species.

4.2.4.7 Synopsis of 2020-2030

Predicted changes in bottom temperatures below 200 m, the habitat for this species, are going to be less than natural variability and are not thought to bring noticeable change to the populations in the Atlantic LAB.

4.2.4.8 Synopsis of 2060-2070

Predicted changes in bottom temperatures below 200 m, the habitat for this species, would bring average temperature in the deep channels of the GSL close or even above 6 °C, the probable TpII for this species. Furthermore, although adult GSL Greenland halibut are very hypoxia tolerant, the juveniles are less so, with an O2crit of about 15% sat. Present DO levels in the estuary, the main nursery, are 18 to 25% sat. and result in a considerable reduction of the AS of juvenile fish. The projected decrease in DO accompanied by increased temperature will decrease AS further. The GSL population is likely to suffer a loss of productivity, reduced abundance and distribution, even possible extirpation. Populations off Newfoundland and Labrador enjoy colder temperatures at present and would be less impacted by the predicted warming of bottom waters.

4.2.5 Haddock

4.2.5.1 Background

Haddock, *Melanogrammus aeglefinus*, is a Gadoid found on both sides of the North Atlantic. On the western side, it is abundant from the southern part of the Grand Bank to Cape Cod (Bigelow and Schroeder, 1953). It is found in low numbers in the southern GSL, but also in the St. Lawrence Estuary, the northen GSL, and off the east coast of Newfoundland (Bigelow and Schroeder, 1953; Scott and Scott, 1988). Haddock can be found as far north as Western Greenland (DFO, 2012b), but this is an extension of the Iceland stock (Stein, 2007) with no connection with the haddock populations of the Atlantic LAB. Haddock move further south during winter, reaching Cape Hatteras (Bigelow and Schroeder, 1953). Spawning ground are Georges Bank, the GM, north of Cape Cod, Browns Bank and Sable-Emerald Bank on the SS, St-Pierre Bank and the southern Grand Banks (Bigelow and Schroeder, 1953; Page and Frank, 1989). There is little exchange between adjacent stocks (DFO, 2012b), at least for adults. Egg and larval drift makes mixing and range extension (in response to warming) possible.

Haddock is an important commercial species. Even though it is caught in large numbers only in the southern part of the Atlantic LAB, it ranked first in landings and third in value among demersal fish in 2011.

Despite many similarities in biology and habitat choice with Atlantic cod, haddock inhabits a more restrictive depth range (~30 to 350 m, Bigelow and Schroeder, 1953; Scott and Scott, 1988; DFO, 2012b). They are found at depth > 145 m in winter, and move to shallower water (25–125 m) in summer (Scott and Scott, 1988). Haddock is also more selective of sediment type than cod. Haddock are rarely caught over ledges, rocks, or kelp, or on the soft oozy mud. It prefers gravel, pebbles, clay, smooth hard sand, sticky sand of gritty consistency and broken shells (Bigelow and Schroeder, 1953; Scott and Scott, 1988).

4.2.5.2 Temperature

Haddock is usually found within 1–13 °C (Bigelow and Schroeder, 1953; Scott and Scott, 1988). They inhabit warmer waters in summer (4–8 °C) than in winter (2.3–3.4 °C) (Scott and Scott, 1988). Gonad maturation starts in August for females and October for males (Waiwood and Buzeta, 1989). On the SS, gonad maturation takes place at 3–9 °C, but there is a shift to colder temperatures prior to spawning (1–5 °C) (Waiwood and Buzeta, 1989). This is accomplished by a move to shallower waters (75–180 m during early maturation vs. 35–110 m during ripening and spawning). Spawning takes place between 2 and 10 °C, most often between 2.5 and 6 °C (Bigelow and Schroeder, 1953; Page and

Frank, 1989). This is much colder than for European haddock (5–10 °C) (Bigelow and Schroeder, 1953).

On Georges Bank, the time of peak spawning correlates with SST: peak spawning occurs when water reaches 2–10 °C (Page and Frank, 1989). This suggests that the temperature of the water masses occupied near the time of spawning and where gonad maturation takes place is influenced by SST. In addition to this interannual variation in spawning time within site, there is a gradient (southwest to northeast) in spawning time between sites (Page and Frank, 1989), with ~2–3 months difference between Georges Banks and the southern Grand Bank.

The eggs are buoyant. Egg development time is very slow below 2 °C, and increases rapidly with temperature between 2 and 8 °C (20–25 vs. 10–15 days, respectively (Page and Frank, 1989; Martell et al., 2005). This compares well with Scott and Scott's (1988) estimates: 25–32 d at 2.5 °C, 13–24 d at 5 °C and 9–12 s at 10 °C. The rate of development continues to increase, but slowly, between 8 and 16 °C (Page and Frank, 1989). Hatching success has been assessed within the 2–12 °C range and was best at intermediate temperatures (Laurence and Rogers, 1976). Together, these studies suggest that temperatures of 4–8 °C are optimal for eggs.

The rate of development of larvae increases with temperature within the range 2–10 °C (Laurence, 1978; Martell et al., 2005), and larval length at the time of yolk sac resorption is not influenced by temperature (Martell et al., 2005). Therefore, warmer temperatures during larval development should be advantageous (increased probability of survival because of shorter duration of the larval stage), as long as food is not limiting: Buckley et al. (2004) found that the greatest growth rate of larval haddock on Georges Bank was at 7 °C, and suggested that food limitation reduced growth rate at higher temperature. They warn of a possible negative effect of ocean warming on larval development in this species.

The growth rate of juvenile (~ 4 g) haddock has been measured in the laboratory at 8 and 12 °C, as a function of feeding rate (Peck et al., 2003). Growth rate was greater at 12 °C, but gross growth efficiency (growth per unit of food consumed) was better at 8 °C.

4.2.5.3 Dissolved oxygen

There is no information on hypoxia tolerance in haddock. However, as it is uncommon below 225 m, hypoxia is only a problem for a small proportion of the population inhabiting depths of 175 to 225 m. This proportion could increase due to the projected worsening of hypoxia in the deep channels of the Atlantic LAB and probably also in the waters that bathe the continental slope, but haddock could probably adapt to avoiding waters deeper than 175–200 m if hypoxia became too severe below such depths.

4.2.5.4 pH

There is no information on the possible impact of ocean acidification on haddock.

4.2.5.5 Salinity

In the GM, haddock is found at salinities of 31.5 to 34, but mostly above 32, and spawn at salinities of 31.5–33.5 (Bigelow and Schroeder, 1953). Water density varies from 1.0255 to 1.0270, which makes the eggs buoyant (Bigelow and Schroeder, 1953). In the laboratory, egg hatching success decreased when salinity was lower than 30 (Laurence and Rogers, 1976).

4.2.5.6 Conclusions

Haddock will likely benefit from any warming of the Atlantic LAB. Cold temperatures prevent it from being abundant in all but the southernmost part of the LAB at the moment. The fact that spawning date is partly influenced by SST in the spring (Page and Frank, 1989) reduces the risk of mismatch between haddock larvae and their prey due to the projected earlier spring blooms in future years. It is not clear if warming will have a negative impact on recruitment in the southern part of the Atlantic LAB: field data suggest growth rate is limited by prey availability when larvae are in waters warmer than about 7 °C, but spawning could occur earlier (and at similar temperatures to the present) as an adaptation to earlier springs.

4.2.5.7 Synopsis for 2020-2030

Projected increases in the variability of spring timing and SST may result in increased variability in recruitment, although this species can adjust spawning time to local temperature conditions, which will buffer the increased variability in spring conditions. No change in the distribution of the stocks is anticipated on this time scale because the adults show site-fidelity and even the southern part of the Atlantic LAB is not expected to become too warm for haddock within 10–20 years.

4.2.5.8 Synopsis for 2060-2070

Projected increases in SST may favour larval development, future SSTs being closer to the optimal temperatures for egg and larval development. Risk of mismatch between larvae and their prey due to projected earlier springs is low for this species because spawning time is not only controlled by bottom temperature, but also by SST. Larval growth rate will only improve if there is an adequate food supply, which is not always the case during warm years at present. Projected increases in bottom temperatures and warming and thinning of the CIL would make the GSL as well as the rest of the Grand Banks a better habitat for juvenile and adult haddock than at present, and these habitats which are marginal at present could become important haddock habitat with ocean warming. True range extension (Labrador shelf) may be slow as the Labrador Current would make it difficult for eggs and larvae to drift north, and adults are known not to move much.

4.2.6 Redfish

4.2.6.1 Background

Redfish or ocean perch is not a species but a common name for 3 morphologically similar species. Two of them are 'beaked redfishes', the Acadian redfish (*Sebastes fasciatus*) and the Deepwater redfish (*S. mentella*) (Scott and Scott, 1988; Pikanowski et al., 1999). The third species is *S. marinus*. Because of the difficulty in distinguishing them, they are managed as one species. Redfish are found on both sides of the Atlantic, although *S. fasciatus* is only found on the western side (Sévigny et al., 2007). In the northwest Atlantic, they range from Baffin Island to waters off New Jersey (Pikanowski et al., 1999; Gascon, 2003). *S. marinus* is only common on Flemish Cap. Beaked redfish are dominant on the Labrador shelf. Conversely, only *S. fasciatus* occurs in the south (GM). Elsewhere, the two species co-occur, although *S. mentella* is generally distributed deeper than *S. fasciatus* (Ni and Sandeman, 1984; Pikanowski et al., 1999; Sévigny et al., 2003). The exception to this general trend is the GSL where *S. mentella* dominates (Gascon, 2003). The hybrid *S. fasciatus* x mentella is also common in, but restricted to, the GSL and the Laurentian Channel (Sévigny et al., 2003).

Redfish are fished in the entire Atlantic LAB where depth is sufficient (usually > 200 m), including the three deep channels within the GSL, the Laurentian Channel south of Newfoundland, and the continental edge around the Grand Banks, including the Flemish Cap, and the Labrador Shelf (Gascon, 2003; Sévigny et al., 2007). For management purposes, three units are considered. Unit 1 is the Gulf of St. Lawrence, unit 2 is off Newfoundland's south coast, and unit 3 is SS-GM (see map in Gascon, 2003, Fig. 1.1, p. 9). Redfish occur in shallower water in the GM, possibly owing to the availability of 2–8 °C closer to the surface, or to the fact that it is *S. fasciatus* territory, or both. Prior to the mid-1980s, it was the second most important groundfish species in the northwest Atlantic (Ni and Sandeman, 1984), but in 2011, it ranked 3rd in landings and 5th in value in the Atlantic LAB among groundfish species. The drop is mostly due to the very large decline observed in the GSL (management unit 1), which has been under a fishing moratorium since 1994, but landings have generally been much lower after the 1980s in all areas. The declines are attributed to overfishing and a long interval without strong recruitment, recruitment being highly variable in this species (Sévigny et al., 2007). Stock structure is complex. Units 1 and 2 form one population for each of the two species of beaked redfishes. Unit 3 and 3LNO are distinct from each other and from units 1+2. *S. mentella* in the northern part of the range are separate from those of other areas, and there appear to be two different populations off Labrador, each using a different depth range (Valentin, 2006; Sévigny et al., 2007). This suggests that circulation patterns prevent larval exchanges between populations.

Redfish have a slow growth rate and are long lived, some specimens having been aged to at least 80 years (Pikanowski et al., 1999; Gascon, 2003). They usually take 8 to 10 y to reach commercial size (25 cm) (Gascon, 2003). *S. fasciatus* has a slower growth rate than *S. mentella*. For each species, there is a north-south gradient in maturation size, with specimens caught further south maturing at a smaller size (Ni and Sandeman, 1984).

Redfish are found along the slopes of banks and deep channels in depths of 100–700 m (Atkinson, 1989b; Pikanowski et al., 1999; Gascon, 2003). According to Scott and Scott (1988), *S. fasciatus* is most numerous between 128 and 366 m, *S. mentella* between 350 and 700 m, and *S. marinus* between ~300 and ~400 m. In the GM, where there is a thermocline but no CIL, redfish can occur in shallow water during winter, whereas the warm surface layer excludes them from such waters in summer (Klein-MacPhee and Colette, 2002). Small redfish tend to occupy shallower waters than large redfish (Atkinson, 1984).

Redfish undergo seasonal migrations (Atkinson, 1989b). Perhaps the most extensive migrations concern unit 1, as redfish move to the southestern part of the GSL and also out of the GSL into unit 2 for the winter (Atkinson, 1984).

They prefer rocky or clay-silt bottom types and are less common on sand (Scott and Scott, 1988; Klein-MacPhee and Colette, 2002). Juvenile and adult fish are known to make vertical migrations, rising in the water column at night to feed (for a review, see Atkinson, 1989a).

Redfish are ovoviviparous and fertilisation is internal. Mating takes place in autumn (October to January). Females give birth to live offspring in April-May for *S. marinus*. Spawning is a bit later for the beaked redfishes (March to July) (Scott and Scott, 1988; Klein-MacPhee and Colette, 2002). Where the two species of beaked redfishes cohabit, *S. mentella* release their young a month earlier than *S. fasciatus* (Gascon*, 2003)*. The depth at which larvae are released is not known, but is almost certainly below the thermocline. In the GM, 5–6 mm larvae (likely of *S. fasciatus*) are found within the first 10 m of the water column (Kelly and Barker, 1961). In July and August, the 10–15 mm larvae move deeper to ~20 m; they appear to remain there, within the thermocline, until they reach ~25 mm (Kelly and Barker, 1961). At this time (September), they move below the thermocline in cooler water (~6 °C at 60–100 m) (Kelly and Barker, 1961). Their sojourn in the thermocline in late summer may allow them to adjust to their preferred temperature with little vertical movement (Kelly and Barker, 1961). Larvae are planktonic for about 4 months (Pikanowski et al., 1999). The duration of the pelagic period could permit dispersion and mixing over large distances, but this does not seem to be the case (see below).

4.2.6.2 Temperature

Redfish occur on both sides of the Atlantic Ocean in cool waters (0–13 °C, but mostly 3–8 °C) (Klein-MacPhee and Colette, 2002; Gascon, 2003). An analysis of the catches in research surveys for the period 1970–1995 showed that redfish in management unit 2 (Laurentian Channel outside the GSL) occupy colder temperatures than those in unit 3 (SS and GM) (4–6 vs. 5–9 °C, respectively), despite occupying similar depths (mostly 125–300 m, usually > 200 m in unit 2 and < 200 m in unit 3) and salinities (33–35, mostly > 34) (Smith et al., 2003). The annual thermal regimes (annual cumulative degree-days) were also calculated and redfish from unit 2 had the fewest degree-days, followed closely by those of unit 1. Fish from unit 3 had considerably more degree-days than those of the other 2 units (Smith et al., 2003). Along the northeastern edge of the Grand Banks, redfish are found within 2–4.9 °C, at depths of 250–450 m (with some seasonal movements) (Atkinson, 1989b). In the GM, juveniles are found within 3–13 °C in the spring, and 4–14 °C in autumn, but most juveniles are at 5–10 °C (Pikanowski et al., 1999). Still in the GM, adults are found at 4–12 °C in spring and 4–13 °C in autumn. Similarly to juveniles, most fish are found at 5–10 °C (Pikanowski et al., 1999). In their review, Klein-MacPhee and Colette (2002) report preferences of 2.8–8.3 in the GM, 7 °C in the GSL, 5–9 °C on the SS. Dutil et al. (2003) studied the behaviour of adult *S. fasciatus* in a temperature gradient. Their preliminary analysis shows that the fish, acclimated to 2 °C, distributed themselves mostly within 0.5 and 2 °C (the duration of the experiment is not given).

In the GM, larvae are found at temperatures of 3 to 15 °C, but mostly at 6–11 °C (Pikanowski et al., 1999). In the laboratory, the survival rate of recently spawned *S. fasciatus* larvae was assessed after 96 hours exposure at different temperatures within the range 0–20 °C. Survival was best between 2 and 10 °C (Dutil et al., 2003). Decreased survival in the range ~0.5–2 °C could indicate that in all parts of the Atlantic LAB with a CIL reaching very cold temperatures (essentially all but the southern part of the SS), some larvae will die when going through the CIL to reach the surface layer. Survival decreased rapidly between 12 and 20 °C, and was almost nil above 18 °C (Dutil et al., 2003).

4.2.6.3 Dissolved oxygen

There is no information on hypoxia tolerance in redfish. However, they must face hypoxia south and west of the Grand Banks, due to their depth range and the strong influence of the North Atlantic Central Water (Gilbert et al., 2005). Hypoxia is much more severe in the deep channels of the GSL (unit 1) and DO levels have declined by half between the 1930s and the 1980s (Gilbert et al., 2005). This is also where the decline in abundance after the 1980s has been particularly marked, but it is not known if the two events are linked. Hypoxia has remained stable (and severe) since the mid-1980s (Galbraith et al., 2013)

4.2.6.4 pH

The impact of water pH on redfish physiology is unknown, despite the fact that this species lives in the deep waters of the GSL and the St. Lawrence Estuary, where pH is already as low as 7.7 (Mucci et al., 2011; Chabot and Gilbert, 2013).

4.2.6.5 Salinity

Redfish occur at high salinities only. For instance, an analysis of the catches in research surveys for the period 1970–1995 showed that redfish in management unit 2 and 3 are found at salinities of 33–35, mostly > 34 (Smith et al., 2003).

4.2.6.6 Conclusions

In the GM, *S. fasciatus* larvae move down into the water column as they age, presumably to select appropriate temperatures. Assuming that larvae in the rest of the Atlantic LAB, including *S. mentella* larvae, can do the same, this should make them able to adapt to more frequent abnormally warm years, or to increased average SST temperatures, in the future. In most of the Atlantic LAB, the passage through the CIL to reach surface waters is thought to kill some larvae. Warming and shrinking of the CIL should increase survival. Recruitment is highly variable, and the conditions that ensure good recruitment are not known. Considering that strong cohorts have survived for a few years only to disappear (e.g., in the GSL, Sévigny et al., 2007), conditions that influence recruitment may act over a few years.

Juvenile and adult redfish have a rather wide temperature tolerance considering the temperature variation in deep water, and do not appear particularly susceptible to a moderate warming of deep water. Further, they may be able to compensate warming of deep water by changing their depth distribution to shallower water, closer to the CIL. In summer, redfish from GM cannot use this strategy as there is no CIL, and must move to greater depths to avoid the warming taking place in the top of the water column. In the future, they may be negatively impacted upon if the deep water warms too much. Redfish from this area are more at risk of facing a reduction in available habitat.

The complex structure of different species and different populations that form 'redfish' makes it more difficult to predict the possible effects of global warming in terms of the number of populations that will remain and their distributions. One example is the GM, where the possibility of habitat reduction was raised in the previous paragraph. The impact of this reduction may be more important than the erosion of the southern edge of the distribution of a single species, such as cod, not only because the GM is home to a large redfish stock, but because this is almost entirely made of *S. fasciatus*, and furthermore, it is the bulk of the *S. fasciatus* found in the northwest Atlantic.

4.2.6.7 Synopsis for 2020-2030

In the short term, increased variability in environmental conditions is expected. Redfish should not be particularly vulnerable to such variations. Young larvae appear to have the ability to avoid extremes in SST by moving down the water column. More variable conditions in spring and summer may negatively (or even positively) impact the already variable recruitment. Gonad maturation, egg development and the first larval stages take place in deep waters. Thus there is risk of mismatch between the arrival of the larvae in surface waters and the abundance of their food supply (Chabot and Gilbert, 2013; Loder et al., 2013).

Temperatures at the depths where juvenile and adult redfish occur do not vary much, and this is not expected to change in the short term.

4.2.6.8 Synopsis for 2060-2070

Projected increases in SST may have a negative impact on survival of redfish larvae in regions (e.g., GM, southwest of SS) where they will exceed 8–10 °C in June and July. However, the impact could be less than expected because larvae move deeper into the water column as they age, and the projected warmer springs should result in earlier spawning and thus they should move deeper earlier during the summer than at present. However, there is a risk of mismatch between larvae and prey, because maturation takes place in deep water and larvae feed in surface waters, and both are expected to warm at different rates (Chabot and Gilbert, 2013; Loder et al., 2013). Most of the Atlantic LAB is characterized by a permanent CIL. Projected warming and thinning of the CIL may improve the survival of larvae, which must cross the CIL to reach surface waters. Recruitment is highly variable at present, but the factors influencing recruitment are poorly understood, and it is impossible to say if recruitment will improve or deteriorate with ocean warming.

The projected increase in deep water temperature may bring many populations of juveniles and adults to the upper part of their preferred temperature range. Redfish could possibly adjust its depth distribution to compensate this increase in temperature. If they experience warming, the present latitudinal gradient suggests that size at maturity will decrease, although part of this gradient is due to species composition, not just temperature, and the future species and population structure is impossible to predict. South of the Atlantic LAB, the heart of *S. fasciatus* distribution may suffer from habitat contraction because of warming of surface waters and bottom waters, and the absence of a CIL that could have acted as a refuge. It is not known if this population's range will shrink or if it will start to expand and mix with populations in units 1 and 2 and 3LNO. Presently juveniles and adults of these different populations do not mix, and larvae do not seem to drift between populations.

Redfish in units 1 and 2 will face a projected worsening of hypoxia. Hypoxia is already severe at the head of the 3 main channels in the GSL (18–25% sat.) and is expected to worsen. This will be accompanied by warmer temperatures and thus an increase in metabolic rate and oxygen requirements of redfish. Their tolerance to hypoxia is unknown. Redfish from the GM and 3LNO will also face a worsening of hypoxia, though the situation there will be much less severe than in the GSL.

The fact that multiple species are involved, low population levels in many populations, highly variable recruitment, slow growth rate and the limited connectivity among suitable habitats are factors that contribute to the lower adaptability of redfish to climate warming.

4.3. PELAGIC FISHES

4.3.1 Atlantic Herring

4.3.1.1 Background

Atlantic herring (*Clupea harengus*) is a schooling pelagic fish found on both sides of the northern Atlantic (Scattergood and Tibbo, 1959). Its range in the northwest Atlantic extends from Labrador to Cape Hatteras (Scott and Scott, 1988), although the most important stocks are north of Cape Cod (Scattergood and Tibbo, 1959). Spawning is limited to SS-GM in the south and northern

Newfoundland in the north (Melvin et al., 2009a). Eggs are deposited on the substrate or on macrophytes in 10–80 m of water and strong currents (Reid et al., 1999). Larvae, juveniles and adults are pelagic but make circadian vertical migrations (Reid et al., 1999).

It is by far the most important pelagic fish in the Atlantic LAB in terms of landings and value. It also plays an important energy transfer role in the ecosystem, feeding predominantly on copepods, euphausiids, chaetognaths and capelin (Checkley Jr, 1982; Reid et al., 1999; Darbyson et al., 2003; Savenkoff et al., 2006c) and being fed upon by numerous fish, bird and mammal predators (Reid et al., 1999; Savenkoff et al., 2006c; Overholtz and Link, 2007; Guénette and Stephenson, 2012).

The species show very high plasticity of life history traits as a response to environmental variations. As a consequence, this species is an interesting case of integration of multiple factors influencing various aspects of their life history and dependent on prevailing set of conditions in the different seas (Dickey-Collas et al., 2010). Life history traits such age at maturity, growth and fecundity show a latitudinal gradient linked to temperature, but in addition may be density-dependent (Reid et al., 1999). Colder water populations live longer, grow more slowly but to a larger size than warmer water populations (Brunel and Dickey-Collas, 2010). For instance, herring from the GM reach maturity earlier (2-4 years old) than in Newfoundland (3-6 years old) (Trenkel et al., 2013). In addition to temperature, food availability and density dependence effects have been noted in several areas around the world (Trenkel et al., 2013).

The Northwest Atlantic herring stocks are considered as a complex of discrete spawning units that show fidelity to their spawning grounds (Stephenson et al., 2009) as a result of imprinting or as a learned behaviour to maximize the probability of spawning in good nurseries (McQuinn, 1997). Migrations between summer feeding, overwintering, and spawning grounds cover considerable distances within short periods and are predictable from year to year although the location of summer feeding areas varies with the availability of food (Stephenson et al., 2009; Stobo and Fowler, 2009). More northerly populations migrate south in winter to avoid very cold water (Trenkel et al., 2013).

Both overfishing and changes in environmental conditions have been proposed as determinants of population dynamics and migration behaviour in all Atlantic and Pacific populations (Dickey-Collas et al., 2010). Most stocks around the world have been depleted and then recovered from overexploitation, but in the NW Atlantic, herring stocks from Georges Bank, and SW Nova Scotia have not fully recovered to historical biomass levels (Stephenson et al., 2001; Melvin and Stephenson, 2007; Power et al., 2010).

Despite the plasticity of life history traits with environmental conditions and stock status, herring stocks have shown that a combination of overfishing and bad environmental conditions can lead to collapse and prolonged recovery, which may only be partial. Changes in migration patterns and food availability could cause major changes in fisheries practices and management. Winters and

Wheeler (1987) proposed that these stocks should be managed with caution, at low fishing mortality, using a threshold of fecundity to detect overfishing and that exploitation be stopped when conditions were too severe. These recommendations are still relevant and even more so when considering the herring play an important role in the ecosystem as forage fish (Guénette and Stephenson, 2012).

4.3.1.2 Temperature

Atlantic herring populations have a relatively wide temperature tolerance for spawning (4–15 °C) (Petitgas et al., 2012). Laboratory studies confirmed that eggs develop normally at 10 and 15 °C, but not at 0 and 5 °C. At 20 °C, rapid initial development is followed by 100% mortality (Reid et al., 1999). Herring larvae can grow in 2–21 °C, although food can be limiting at high temperature, when metabolic rate is higher.

T_{cI} and T_{cII} (lethal temperatures) for juvenile herring are -1.1 and 19.5–21.2 °C, respectively, and the preferred temperature is 8–12 °C in the laboratory (Reid et al., 1999). For GM herring, sustainable yield is higher at 7.9 than at 6.5 °C, at any level of fishing mortality (Anthony and Fogarty, 1985), suggesting a greater productivity at the higher temperature.

Herring show a latitudinal gradient in reproductive behaviour in the western Atlantic (mainly spring spawning in the north to fall spawning in the south). The prevalence of each spawning strategy has recently shifted in northern areas along with the relative contribution of fall spawning events to annual recruitment (Melvin et al., 2009a). These changes are coincidental with an increase in mean water temperature although the mechanism for this is not well understood and changes in fisheries management may confound observations. This trend suggests that the fall spawning component of northern stocks will increase with water temperature and that the spawning range is likely to shift northward over time (Melvin et al., 2009a). In fact, the trend toward fall spawning is persisting in Newfoundland (G. Melvin, DFO St. Andrews, pers. comm). Herring stocks presently at their southern limit of the species' tolerance such as the GM could potentially disappear over time while other southern stocks would see their productivity declining.

The Newfoundland spring spawning stocks, at the northern range of the species distribution, show a link between recruitment success and the temperature and salinity during winter (Winters and Wheeler, 1987). The stock recruitment relationships of the Ricker type, suggest a density-dependent relationship. It is unlikely that the productivity of these stocks will be adversely impacted by warmer temperature. Part of the response will depend also on the composition and productivity of zooplankton in each area (Melvin et al., 2009b).

Warmer winter temperatures may influence the timing and distance of seasonal migrations. There is already some evidence of changing migration patterns on both sides of the Atlantic that appear linked to changes in abundance and maybe warmer water (Trenkel et al., 2013).

4.3.1.3 Dissolved oxygen

Even though they are pelagic and the surface layer is not hypoxic in the Atlantic LAB, herring encounter hypoxic waters in other parts of the world, such as the Kattegat and Baltic Sea. In the Baltic, herring avoids areas where DO level is < 50% sat. (Neuenfeldt, 2002). In the laboratory, lowering DO down to 15–30% sat. increases swimming speed (Domenici et al., 2000; Domenici et al., 2002), but without increases in lactate (Herbert and Steffensen, 2006). This is interpreted as an escape response, without the need to increase anaerobic metabolism. This pelagic species likely needs to maintain an important level of AS compared to demersal fish. Only the most severe hypoxic zones in the Atlantic LAB (the St. Lawrence Estuary and the heads of the Esquiman and Anticosti channels in the GSL) might become problematic for herring, although increased metabolic rate accompanying warmer temperatures in 50–60 years may force herring to avoid spending time below the CIL in the deep channels of the GSL.

4.3.1.4 pH

There is no information on the possible impact of ocean acidification on herring.

4.3.1.5 Salinity

Atlantic herring can spawn from 4 to 35 salinity units, and the larvae also tolerate a wide salinity range (Petitgas et al., 2013). Laboratory studies indicate a general preference for salinity of 26–32, although this is temperature dependent, higher salinity being preferred at temperatures < 10 °C (Reid et al., 1999). Changes in salinity projected for 10–20 years and 50–60 years are unlikely to be a problem.

4.3.1.6 Conclusions

Using a conceptual model linking the proportion of spring and fall spawners of northwest Atlantic herring stocks, Melvin et al. (2009a) predicted that an increase in water temperature (SST) may obliterate some of the inshore spawning populations in the GM, especially in the western portion, and that the probability of successful reproduction on Georges Bank would likely be reduced, leading to a substantial reduction in biomass of this stock complex. The Bay of Fundy/coastal Nova Scotia (4WX) autumn-spawning herring would become less abundant and spring-spawning herring may disappear completely.

In the GSL, these authors predicted a shift towards autumn spawners, and some spring-spawning components are likely to disappear, whereas others would be reduced. However, the reduction in spring spawners may not be compensated by an increase in autumn spawners, given the low water temperatures during severe winters. It is not clear if these authors anticipated as high a rate of warming in the GSL as projected by the Trends and Projections Group: less severe winters may then allow autumn spawners to be more successful and compensate for the decrease in spring spawners. According to Melvin et al. (2009a), the eastern Gulf may see the least change and actually prosper. The conditions there would permit a balance of spring and autumn spawners.

Warming trends in SST for the Labrador Shelf should permit a northward extension of herring, including new northerly spawning sites. The species can establish new spawning sites (McQuinn, 1997) and move long distances. However, Melvin et al. (2009a) believed that the proportions of spawning types may undergo some drastic changes, similar to those predicted for the eastern GSL: there could be a continued deterioration of the spring-spawner component and an increase in the autumn spawners. Whether or not spring spawners will establish north of southern Labrador remains to be seen. Northerly populations may move less far south during the winter.

4.3.1.7 Synopsis for 2020-2030

Projected increases in SST may favour larval development as herring larvae prefer warmer temperatures (4–15 °C). Widespread dispersal due to pelagic nature of larvae also increases this species' ability to adapt or move away from unfavourably warm areas. Lack of significant differences between adult spawning, egg and larval environments reduces the risk of phenology mismatch.

No habitat specificity, high mobility and wide temperature range (0-18 °C with distribution from Newfoundland and Labrador to South Carolina, USA) make Atlantic herring juveniles and adults fairly insensitive to warming. Projected increases in SST should have little impact on herring habitat from GM northward, as its maximum tolerable temperature is not exceeded by projected SSTs for the next decade or two. Atlantic herring my retreat from the southern-most reaches of their distribution however. High mobility and efficient dispersal make herring able to escape unfavourable conditions.

4.3.1.8 Synopsis for 2060-2070

Projected increases in SST may favour larval development, because herring larvae prefer warmer temperatures (4–15 °C). Widespread dispersal due to pelagic nature of larvae also increases this species' ability to adapt or move away from unfavourably warm areas. Lack of significant differences between adult spawning, egg and larval environments reduces the risk of phenological mismatch.

Low habitat specificity, high mobility and wide temperature range (0-18 °C with distribution from Newfoundland and Labrador to South Carolina, USA) make juveniles and adults fairly insensitive to warming. Projected increases in SST should have little impact on herring habitat north of the GM, as its maximum tolerable temperature is not exceeded by projected SSTs for +50 years. However, temperatures may not be tolerable in summers south of GM, so these areas may suffer. High mobility and efficient dispersal make it able to escape unfavourable conditions.

4.3.2 Atlantic Mackerel

4.3.2.1 Background

The Atlantic mackerel (*Scomber scombrus*) is found on both sides of the northern Atlantic, between latitudes of ~30 to ~50°N, with no exchange between the two sides (Sette, 1943; Scott and Scott, 1988). In the northwest Atlantic, its range extends from Cape Lookout, NC, to Black Island, Labrador (Scott and Scott, 1988).

Atlantic mackerel is an important commercial species, ranking 3rd in landings and 2nd in value among pelagic fish in the Atlantic LAB. The stock is currently at a low level of abundance, due to several years of unsustainably high fishing mortality (DFO, 2012a). This is a fast-swimming species which undergoes extensive seasonal migrations (Sette, 1943; Scott and Scott, 1988; Colette, 2002).

There are two spawning aggregations. The southern GSL is the main spawning area of Atlantic mackerel in Canadian waters (Sette 1943, Arnold 1970), with some spawning occurring also on the SS and along the Newfoundland south coast (Sette, 1943; Grégoire et al., 2013). The second mackerel aggregation spawns in the Mid-Atlantic Bight and in the GM (Sette, 1943; Colette, 2002). Because the two populations mix in winter along the continental shelf, where there is an important winter fishery for mackerel, they are managed as one stock (Studholme et al., 1999).

Generally speaking, mackerel is present in the Atlantic LAB only during summer and fall, to spawn and feed (Sette, 1950; Scott and Scott, 1988). Those that spawn on the SS do so starting in the middle of June. At the main spawning site, the southern GSL, eggs are found from late May to mid-August, but the height of the spawning season is from mid-June to mid-July (Sette, 1943). After spawning, mackerel disperse to feed in the parts of the Atlantic LAB where waters are sufficiently warm (i.e., up to southern Labrador).

In summer, Atlantic mackerel is in the upper water layers, mostly waters shoaler than 46–55 m (Colette, 2002). It forms large schools of fish with similar size (and age), younger fish usually keeping closer to the coast (Sette, 1950). In autumn, the Atlantic mackerel migrates back to waters at the shelf edge, at moderate depth (70–200 m), from the southern edge of Georges Bank down to Cape Hatteras (Sette, 1950). It is possible that some fish remain further north, up to Sable Island (Sette, 1950; Colette, 2002).

Copepods, hyperiid amphipods and euphausiids are the staple of the mackerel's diet. They also feed on chaetognaths, many shrimp species, larvae (crustaceans, molluscs, fishes) and fish. Larger fish eat larger prey, including squids, silver hake, sand lance, capelin, herring and sculpins (Studholme et al., 1999; Colette, 2002; Darbyson et al., 2003; Savenkoff et al., 2005). Feeding is more intense in the summertime and mackerel condition (fat content) increases from a minimum in April to a maximum in August (Sette, 1950). Sea birds, marine mammals, sharks, squids, cod and other fish prey on Atlantic mackerel, especially juvenile fish (Studholme et al., 1999; Colette, 2002; Savenkoff et al., 2005).

4.3.2.2 Temperature

Laboratory studies show intolerance of temperatures < 5–6 and > 15–16 °C, and lethal temperatures of 2 (T_{cl}) and 28.5 °C (T_{cII}) (for reviews, see Overholtz et al., 1991; Studholme et al., 1999). In winter, Atlantic mackerel select temperatures within the 5–13 °C range (Studholme et al., 1999; Overholtz et al., 2011), the lower limit being ~2 °C colder than described by Sette (1950), though Sette also observed what he called "stragglers" down to 4.5 °C. In the spring, adults of the southern aggregation (spawning in the GM) can be found at temperatures of 2 to 14 °C, but most are within 5 to 13 °C (Studholme et al., 1999). Summer temperatures sought by mackerels in the GM range from 4 to 20 °C, with most fish occupying temperatures of 10 to 14 °C (Studholme et al., 1999; Colette, 2002). In the GSL, mackerel can be found in waters as cold as 4 °C, but they usually select waters > 7 °C (Castonguay et al., 1992).

Water colder than ~7 °C forms a barrier to the northward progression of migrating mackerel in spring (Sette, 1950; Trenkel et al., 2013), although the presence of warmer water does not necessarily make mackerel migrate earlier (Sette, 1950). There can be exceptions to this general trend, as D'Amours and Castonguay (1992) observed mackerel migrating through Cabot Strait on the same dates as usual during a very cold year, when water was < 3 °C, and concluded that the thermal requirements could be subordinate to the reproductive requirements during the spawning migration. Overall temperature has an impact on the timing of the spawning migration, with spawning taking place earlier during warm springs in the northeastern Atlantic (Jansen and Gislason, 2011). Spawning takes place in relatively warm surface temperature, at least 8 °C, but mostly between 9 and 14 °C (Colette, 2002). In the southern GSL, spawning occurs within the 8.5–13.5 °C range (Sette, 1943; Grégoire et al., 2013) and the peak of spawning occurs at 12 °C (Scott and Scott, 1988).

In plankton surveys, mackerel eggs have been collected at near surface temperatures ranging from 5 to 23 °C, with the largest proportion between 7 and 16 °C (Studholme et al., 1999). In the laboratory, embryonic development rate is proportional to temperature in the range 11 to 21 °C, but hatching success is maximal at 16 °C (Worley, 1933; Colette, 2002). Eggs did not develop normally or died when temperature was ≤ 10 or ≥ 22 °C (Worley, 1933). Typically, water temperature increases as egg develop in the field, so eggs spawned at 8–9 °C may be able to develop if the water warms to 11 °C before the eggs die.

In surveys conducted in the US waters, larvae were found at water temperatures ranging from 6 to 22 °C, with the largest proportion between 8 and 13 °C (Studholme et al., 1999). Juveniles were found at temperatures of 4 to 22 °C, with the majority occurring at 10 to 15 °C in the fall, at 5–6 °C in winter, 5 to 11 °C in spring, and between 8 and 19 °C in summer (Studholme et al., 1999)

4.3.2.3 Dissolved oxygen

Atlantic mackerel have high energy requirements and must swim constantly when water is warm (lower oxygen solubility) to insure maximum oxygen extraction by the gills (Colette, 2002). This high energy demand and the fact that mackerel have not evolved to deal with deep hypoxic water that is typically only found below thermoclines, suggest that they have low hypoxia tolerance.

4.3.2.4 pH

There is currently no information on the impact of acidification on mackerel.

4.3.2.5 Salinity

Most larvae, juveniles and adults are found at salinities > 30, but sometimes down to 25 in estuaries (Studholme et al., 1999). Atlantic mackerel actively select salinities between 32.5 and 34.5 over their winter range (Overholtz et al., 2011). Egg survival may be lower at a salinity of ~23 than at 25–27 (Peterson and Ausubel, 1984).

4.3.2.6 Conclusions

Atlantic mackerel are very responsive to changes in temperature (for a review, see Overholtz et al., 1991). Interannual variations in winter water temperature on the shelf and along the shelf edge result in distributional changes, and the recent warming trend over the Mid-Atlantic Bight and the GM have resulted in a shift north and east by about 250 km in the winter distribution of the stock (Overholtz et al., 2011). In the northeastern Atlantic, this species has been shown to expand its distribution northward (Iceland) and to spawn earlier during warm periods (Jansen and Gislason, 2011; Astthorsson et al., 2012). It is expected that the distribution and biology of the stock will be affected by a long-term warming trend (Overholtz et al., 2011). Therefore, in the Northwest Atlantic, including the Atlantic LAB, both an increase in biomass and an extension in range might be expected for this species. The latter will probably occur on Georges Bank, the Scotian Shelf, and off the coast of Newfoundland (Overholtz et al., 2011).

4.3.2.7 Synopsis for 2020-2030

The greater variability in SST and date of spring onset projected for this period should not impact much on spawning success or on egg and larvae survival, but the timing of spawning could become more variable. SST at spawning time (mostly June and July) is not expected to exceed 21 °C. Embryonic and larval development will improve in warm years. The highly mobile spawners can select optimal conditions and reduce the risk of phenology mismatch.

Mobile juvenile and adult mackerel show no habitat specificity and appear to utilize all zones where the surface layer is within ~4–20 °C, especially those within 5–14 °C, in summer and autumn. They will have access to a greater proportion of the Atlantic LAB during warmer summers. Juvenile and adult mackerels may be excluded from the coastal part of the southern GSL and the eastern and central SS in late summer during warm years, if SST exceed 20 °C.

4.3.2.8 Synopsis for 2060-2070

The increases in SST and earlier dates of spring onset projected for this period should be favourable to spawning and to egg and larvae survival. Spawning is expected to occur earlier. SST at spawning time is not expected to exceed 21 °C. Embryonic development will be faster as SST will be closer to the ideal 16 °C. Larval development will be faster, reducing the period of high vulnerability to predation. There is little risk of mismatch between hatching and prey availability because gonad maturation, embryonic development and planktonic blooms are all influenced by SST and should change at the same rate. Further, the highly mobile spawners can select optimal sites, which may be in regions that are presently too cold (northern GSL).

Mobile juvenile and adult mackerel show no habitat specificity and appear to utilize all zones where the surface layer is within ~4–20 °C, especially those within 5–14 °C, in summer and autumn. The projected warming of SST is expected to extend the summer distribution limit further north onto the Labrador shelf. It is possible the Canadian spawning component will not move as far south in winter. Growth rate and productivity could also improve because the projected temperatures are closer to optimal temperatures (8–14 °C). In late summer and in autumn, juvenile and adult mackerels may be excluded from the coastal part of the southern GSL and the eastern and central SS when SST exceeds 20 °C.

4.3.3 Capelin

4.3.3.1 Background

Capelin, *Mallotus villosus*, inhabits arctic and subarctic zones in the Atlantic and the Pacific (Scott and Scott, 1988; Rose, 2005) and is an important consumer of copepods and euphausiids (Vesin et al., 1981; Carscadden et al., 2001; Savenkoff et al., 2004), although hyperiid amphipods can also be important, at least in the northeast Atlantic (Orlova et al., 2010). It is also an important forage fish occurring in the diet of numerous species of groundfish and marine birds and mammals (Lilly, 1991; Bowering and Lilly, 1992; Frank et al., 1996; Savenkoff et al., 2004; Dwyer et al., 2010; Bernier and Chabot, 2013). Therefore, capelin plays a very important role in transferring energy from primary and secondary producers to the higher trophic levels (Savenkoff et al., 2004). Capelin is commercially exploited in the Atlantic LAB, ranking 2nd in landings, but only 6th in value, among pelagic fish.

The principal centre of distribution of capelin in the Atlantic LAB is the Newfoundland/Labrador shelf (2J3KL) (Scott and Scott, 1988; Rose, 2005). Based on offshore acoustic surveys, capelin abundances declined in the early 1990s in Newfoundland and remained very low (Mowbray, 2012), although it is considered lightly fished on the Canadian coast (Carscadden et al., 2001).

During suitable (warmer) periods capelin has been found as far north as Ungava Bay (e.g., in 1884 and 1959). Such expansion of capelin distribution has also been observed around the world over centuries (Rose, 2005). Conversely, this species has been known to expand its range southward as water temperature cooled down and has been exceptionally reported in the Bay of Fundy in the late 1910s and late 1960s (Frank et al., 1996). More recently, capelin was caught on the eastern Scotian shelf and the southern GSL during the late 1980s and early 1990s, and on Flemish Cap starting in the early 1990s. Based on the rate of egg development, the presence of very ripe adults, and juveniles (on the SS), capelin was probably able to spawn in the newly occupied areas (Frank et al., 1996).

Interestingly, cod did not take advantage of the newly available prey on the Flemish Cap between 1982 and 1992 (Frank et al., 1996).

In addition to the shift in distribution along the Atlantic coast, likely linked to lower temperatures, capelin production was influenced by several interacting factors. The ecosystem structure was profoundly modified by the overall decline in large predators, notably, cod. Thus, predation mortality decreased, probably contributing to higher post-spawning survival. Large cohorts were produced more frequently in the 1990s than in the 1980s, increasing intraspecific competition for zooplankton. On the other hand, the decrease in water temperature probably lowered both zooplankton productivity and thus capelin growth and energy stores. Both the observed decrease in capelin average body length and slower egg maturation (due to lower temperatures) may explain the delay in timing of beach spawning in the 1990s (Carscadden et al., 2001).

Capelin behaviour and biology continued to change dramatically despite warmer water temperatures since 1991. Generally, areas with higher capelin densities contracted compared to the 1980s and declined sharply in NAFO division 2J in the fall. In 2010, these aggregations were located on the shelf edge instead of their usual preferred habitat (DFO, 2011b). Productivity declined as the proportion of mature capelin at age 2 increased since 1999, and growth rates in length and weight were at their lowest in 2009.

Recent ecosystem changes and capelin responses are evidence that several factors are responsible for changes in production and migration in addition to temperature, and although the dynamics are not well understood, zooplankton production may be implicated. It could be hypothesized that a long-term increase in water temperature would probably lead to a shift in capelin distribution and migration patterns. Also, increases in plankton production and temperature are likely to increase capelin growth.

4.3.3.2 Temperature

Globally, capelin occurs between -1 and 14 °C, but they are most often found between -1 and 6 °C (Rose, 2005). Beach spawning occurs at 2–11.9 °C, depending on the location (Bigelow and Schroeder, 1953; Scott and Scott, 1988; Nakashima and Wheeler, 2002; Rose, 2005). Rose (2005) reported that the range for demersal spawning was narrower, about 2–7 °C (usually < 5 °C), but Nakashima and Wheeler (2002) observed demersal spawning from 1.4 to 12.1 °C (usually below 4.5 °C). These differences were likely the result of different dates of spawning between studies (Nakashima and Wheeler, 2002) and the widest temperature interval should be used to describe spawning. Egg development is very slow below 2 °C (Carscadden et al., 1989). Generally speaking, egg development and larval growth benefit from warmer temperature, but only if food is available, which requires onshore winds (Leggett et al., 1984). Best recruitment occurs when onshore winds take place at the time of hatching or before the yolk-sack is resorbed. A combination of high temperature in the gravel (fast larval development) and long stretches of offshore wind can result in high mortality (Leggett et al., 1984). Warmer air (and gravel) temperature in the future will make larvae less tolerant to periods of offshore wind at the warmest beach spawning sites, thus increasing variability in recruitment. This could be mitigated by the fact that capelin are able to switch to demersal spawning when surface water temperature becomes too high (~12 °C) (Nakashima and Wheeler, 2002).

It is known that capelin distribution changes according to temperature anomalies. The presence of capelin in the Bay of Fundy was associated with below normal temperatures (Frank et al., 1996). In the late 1980s and early 1990s, cold temperatures have resulted in an extension of capelin distribution into the southern GSL and eastern SS (Rose, 2005; Grégoire et al., 2005). Rose (2005) has studied the impact of past changes in temperature and distribution changes in capelin. He found that changes in temperature as small as 1 °C were associated with changes in distribution over scales of hundreds of kilometres. Larger temperature changes (several degrees) may result in much larger displacements, including the establishment of new spawning sites and long-lasting distribution extensions.

In the northeast Atlantic, capelin distribution can change from year to year in response to changes in water temperature and prey availability: Orlova et al. (2005) demonstrated that there are many indirect effects of climate on capelin distribution and energy reserves involving the abundance and species of copepod prey.

4.3.3.3 Dissolved oxygen

There are no data on the tolerance of capelin to hypoxia. However, capelin are caught in hypoxic water in the GSL, and typically 25% of the catches take place at depths > 148 m (Bourdages and Ouellet, 2011; Grégoire et al., 2011) and thus at DO levels that could vary from about 50 down to 20% sat. (Gilbert et al., 2005). This suggests a good tolerance to hypoxia. But DO levels are expected to drop further during the next 50–60 years (Chabot and Gilbert, 2013). This and the warming trend may force capelin out of the deep channels of the GSL.

4.3.3.4 pH

We did not find any study dealing with the possible impacts of acidification on capelin. However, they are found at present in the deep waters of the St. Lawrence Estuary, where pH is already as low as 7.7 (Mucci et al., 2011; Chabot and Gilbert, 2013).

4.3.3.5 Salinity

Adult capelin are found within a narrow range of salinities (33–35) (Rose, 2005). Spawning can take place at very low salinity on beaches (7, Bigelow and Schroeder, 1953; 3, Rose, 2005), whereas deep water spawning takes place at high salinity (Rose, 2005). This suggests that changes in salinity projected for 10–20 y and 50–60 y will not impact on capelin.

4.3.3.6 Conclusions

Considering this thermal sensitivity and ability to colonise new habitats, the distribution of capelin is expected to move north as temperatures will increase over the next 50–60 years. Recent invasions in southern zones (southern GSL, eastern SS, Flemish Cap, Newfoundland Banks of late 1980s and early 1990s) are expected to be reverted, and possibly the most southerly traditional habitats (northern GSL, Grand Bank) could suffer lower abundances. Abundance, condition and distribution will also be influenced by biotic top-down (Carscadden et al., 2001) and bottom-up effects (Nakashima and Wheeler, 2002).

4.3.3.7 Synopsis for 2020-2030

In the short term, the projected increase in the variability of environmental conditions may result in increased variability in recruitment, especially that air temperature is more variable than the temperatures in the pelagic and demersal zones inhabited by adult capelin and larvae, respectively. The highly mobile adults may use deep-water spawning sites in extreme years or move out of unfavourable conditions and start using new spawning sites.

Juvenile and adult capelin react very quickly to changes in temperature. They prefer very cold waters and depend on beaches mostly for spawning. They rely on environmental cues and temperature-driven rates of gonadal development to begin spawning and to migrate to spawning beaches. Small distributional changes and increased variability in abundance are expected in the short term.

4.3.3.8 Synopsis for 2060-2070

Significant difference between adult and larval pelagic environment (0–725 m) and beach spawning/egg environment (air temperature) could cause phenology mismatch where capelin spawn on beaches that have become too warm. Warmer beach temperatures could favour egg development and larval growth rate, but the increased metabolic rate will require an adequate food supply, which depends on the prevalence of onshore winds. There is no information at the moment on the prevalence of such winds in the future, as beach orientation is very variable over the Atlantic LAB. It is not known to which degree capelin recruitment will suffer a higher failure rate on unfavourable beaches or if deeper spawning sites will be used more often. Beaches that are presently too cold for capelin spawning will become available to capelin, but are north of the Atlantic LAB.

Juveniles and adult capelin react very quickly to changes in temperature. They prefer very cold waters and depend on beaches mostly for spawning. They rely on environmental cues and temperature-driven rates of gonadal development to begin spawning and to migrate to spawning beaches. Projected SST increases are likely to affect capelin due to their low tolerance for warm temperatures and their spawning habitat specificity. The smaller temperature increases projected for NLSS compared with the rest of the Atlantic LAB suggests that it will remain the center of capelin distribution and capelin could even increase in abundance in this sub-basin. But capelin elsewhere may suffer from reduced abundance and resilience to fishing pressure, possibly even facing extirpation in SS-GM

4.4. CRUSTACEANS

4.4.1 Atlantic Lobster

4.4.1.1 Background

The fishery for Atlantic lobster (*Homarus americanus*) is very important in eastern Canada, ranking 3rd in landings and first in value among exploited marine invertebrates. Lobster distribution extends from southern Labrador to Maryland (Tremblay et al., 2011; Gendron and Savard, 2012). In the northern part of this range (the Atlantic LAB, excluding SS-GM), lobsters are found in coastal waters. However, southern populations (SS-GM and further south) utilize the entire shelf, including the shelf edge, thanks to warmer waters (Tremblay et al., 2011). In all areas, lobsters migrate to deeper waters in winter, but return to shallower waters during spring warm up (Munro and Therriault, 1983; Aiken and Waddy, 1986; Campbell, 1986; Pezzack and Duggan, 1986; Cowan et al., 2007; Tremblay et al., 2011). These migrations likely allow lobster to seek favourable temperatures according to season and to avoid stormy shallow waters in winter (Aiken and Waddy, 1986; Cowan et al., 2007; Tremblay et al., 2011).

There are three pelagic larval stages followed by a post-larval stage which resembles an adult lobster and settles on the bottom. According to laboratory studies, the pelagic phase lasts 3–10 weeks depending on water temperature (MacKenzie, 1988; Tremblay et al., 2011; Gendron and Savard, 2012), although modeling suggests a faster growth rate and shorter pelagic phase in situ (Annis et al., 2007), possibly because of better food quality in situ or selective survival of the fastest growing individuals. They are cryptic (rarely leaving their shelter) until reaching approximately 40 mm in carapace length (CL) (Gendron and Savard, 2012). In most regions, they require approximately 8–10 years to reach commercial size (Collins et al., 2009; Tremblay et al., 2011; Gendron and Savard, 2012).

In almost all parts of the Atlantic LAB, landings and by extension abundances are presently at higher levels than the average since the 1950s and similar to the beginning of the fishery in the late 1800s (Comeau et al., 2008; Tremblay et al., 2011; Gendron and Savard, 2012). In Newfoundland, where water is colder, landings have increased only slightly since the 1950s and are inferior to those from the late 19th century (Collins et al., 2009). Newfoundland landings have been declining since the beginning of the 1990s. Similarly, the North Shore and Anticosti populations in the northern GSL, at the northern limit of the species distribution, show slower growth and high vulnerability to fishing, although the present low exploitation rates are accompanied by an extended size structure (DFO, 2009).

4.4.1.2 Temperature

In the 1980s, Nova Scotia lobster landings were linked to large-scale oceanographic processes influencing shallow and slope water temperature, and wind (Hudon, 1994). The highest landings were recorded for the southwest Nova Scotia and Northern Cape Breton, characterised with less complex shoreline, not aligned with the dominant SW wind, and warm and stable water temperature thus resulting in the highest number of degree-days.

Lobsters are a temperate species found in a large array of temperatures on the Canadian Coast. Juveniles and adults are found within the range < 0 to ~25 °C (Tremblay et al., 2011). The latitudinal temperature gradient in the Atlantic LAB influences size at sexual maturity, which is smaller in warmer temperature, and growth rate, lobster growing faster in warmer water (Aiken and Waddy, 1986). Within each population, seasonal migrations inshore or offshore allow optimization of thermal conditions for moulting and reproduction (Cowan et al., 2007).

T_{pII} is likely ~20–22 °C in this species, as suggested by the fact that heart rate and ventilation rate, two parameters that are key to oxygen delivery to tissues, decline at temperatures > ~22 °C (Qadri et al., 2007). In a thermal-gradient tank, summer-acclimated (12–18 °C) lobster avoided water temperatures higher than 19 °C and lower than 13 °C (Crossin et al., 1998). In other experiments by the same authors, lobster generally avoided temperatures warmer than 20 and lower than 12 °C. Median lethal temperature after 48-h exposure was 25.7 and 30.5 °C in lobster acclimated to 5 and 25 °C, respectively. But this may overestimate long-term T_{cII}: Dove et al. (2005)kept lobster at 23 °C for one month and observed a deterioration in serum chemistry and immunocompetence compared to a control group kept at 16 °C. The Long Island population suffered a large drop in abundance in 1999, especially for egg-bearing females (Howell et al., 2005), which likely have heightened metabolic requirements to ventilate their eggs. August bottom water temperature was well over 20 °C that year (Wilson and Swanson, 2005). A difficulty in obtaining enough oxygen to meet metabolic requirements is not the only problem for lobster in high water temperature. An outbreak of a disease, gaffkemia, occurred in the Long Island population in 1991, another anomalously warm year (Briggs 1991, 1992, cited in Howell et al., 2005), and this disease has been shown to be more virulent at temperatures above 20 °C (Stewart et al., 1969). Further, in the southernmost populations (GM and further south), the latitudinal temperature gradient correlates with the incidence of epizootic shell disease (Glenn and Pugh, 2006). Moreover, the numbers of settled larvae dropped and their mortality in the following three years increased between 1997 and 2003, suggesting an interactive effect of shell disease and larval settlement on pre-recruits (Wahle et al., 2009).

Embryonic development is temperature dependent (Templeman, 1936) and hatching occurs when temperature warms in the spring and reaches 8–13 °C (for a review, see Aiken and Waddy, 1986). Larval lobsters occur in surface waters of 6 to 25 °C. However, increased larval mortality below 6 °C (Aiken and Waddy, 1986) to 10 °C (MacKenzie, 1988) is likely one of the factors controlling the northerly limit of the distribution. T_{optG} for larvae is 15–18 °C (MacKenzie, 1988). Because lobster can regulate the temperature for embryonic development with seasonal migrations and hatching tends to take place in shallow water, where temperature is similar to surface temperature, the risk for mismatch with prey abundance is likely low.

In most regions of eastern Canada, summer thermal conditions are not limiting. During the last few years, however, summer temperatures reached 24-26 °C in August and remained warm as far as October in the central Strait of Northumberland. These conditions can be tolerated by juveniles but incite adults to leave the area, which in turn causes decrease in recruitment in this isolated part of the Gulf (M. Comeau, DFO, Moncton, pers. comm.). In contrast, production increased on the north side of Prince Edward Island where abundance increased and lobsters were recently found in deeper waters (20-40 m) because of warmer waters (M. Comeau, DFO, Moncton, pers. comm.).

4.4.1.3 Dissolved oxygen

Moulting increases oxygen consumption in lobster (Penkoff and Thurberg, 1982). Walking also increases oxygen consumption and walking speed is linearly related to oxygen consumption. At maximum speed, oxygen consumption is four times greater than in a resting lobster (Houlihan et al., 1985). Both moulting success and the walking speed could be compromised if lobsters were exposed to hypoxia, especially in warm water, when metabolic rate is greater and the solubility of oxygen lower.

Two studies used the median lethal concentration method with lobster. Mcleese (1956)studied adult lobster (48-h exposures) and obtained ~2–6, 9–13 and 17–22% sat. at 5, 15 and 25 °C, respectively. Miller et al. (2002) calculated 96-h median levels of 40%, 18%, 13% for larvae, postlarvae and juveniles, respectively, at ~20 °C. The O_{2crit} of adult lobster has also been estimated: 16 and 18% sat. at 5 and 15 °C, respectively (McLeese, 1964; McLeese and Watson, 1968a). There is no study on the impact of prolonged exposure to sublethal low DO levels on locomotory capacity, growth rate and reproduction, but these results suggest that the American lobster is fairly tolerant of hypoxia.

4.4.1.4 pH

European lobster larvae (*Homarus gammarus*) develop less calcified exoskeletons but maintain growth rate under low pH conditions (Kroeker et al., 2010). American lobster larvae react a bit differently: at pH 7.7 (projected in surface waters in 2100), they have a slower growth rate and longer intermoult intervals than at the control pH (Keppel et al., 2012).

Surprisingly, elevated concentration in CO_2 (~2850 ppm or 10 times the pre-industrial level of atmospheric CO_2) increases calcification rates in juvenile American lobster, resulting in thicker carapaces (Ries et al., 2009). Although, building such a thick shell in low carbonate environment may be seen as a positive response, it may come at the cost of other physiological needs in the context of finite energy budgets.

4.4.1.5 Salinity

American lobsters are fairly tolerant of low salinity. In his review, Tremblay (2011) reported that the acceptable range for juveniles and adults is 15–32. However, spring melts or heavy runoffs in shallow estuaries can be problematic, especially for moulting lobsters, because their soft carapace has a greater osmotic permeability than that of hard-shelled lobsters. In the laboratory, larval survival decreases at salinities < 20 (Templeman, 1936). In-situ, however, lobster larvae can alter their depth by actively swimming to avoid low-salinity surface waters.

4.4.1.6 Conclusions

Based on temperature alone, warming should lead to higher production for stocks in the middle of the distribution range (SS, northern GSL, Newfoundland) or at the northerly limit of the distribution (lower Labrador shelf), while it would likely have a negative effect in the warmest parts of the distribution (GM and southern GSL), where summer thermal conditions are already approaching the upper limit of tolerance. Lobster living at the slope edge, in the southern part of the distribution, will face a decrease in DO and in pH. This will likely not be lethal, but the impact on productivity and migration patterns is unknown.

Mismatch between lobster larvae and their food supply does not appear likely, considering that embryonic development is dictated by near-surface water temperature. However larvae might be susceptible to acidification, and recruitment could suffer.

Because bottom temperature is thought to be a key determinant of moulting and duration of shell hardening, climate change could result in soft shell lobsters appearing during the fishing season (J. Tremblay, DFO, Dartmouth, pers. comm.). This would certainly have consequences on the timing of fishing seasons.

4.4.1.7 Synopsis for 2020-2030

Lobster larvae will benefit from higher summer surface temperatures in all regions of the Atlantic LAB except in the southern GSL and GM, where recruitment may fail in extremely warm summers.

Juveniles and adult American lobsters are not predicted to loose habitat with projected SST increases over next 20 years, although exceptionally warm summers could result in disease outbreaks in the warm populations of the Atlantic LAB (southern GSL, GM).

4.4.1.8 Synopsis for 2060-2070

Summer temperatures will likely be too warm for larvae in the southern GSL and GM, and lack of recruitment may be one of the factors causing the decline of these populations. Lobster larvae should benefit from faster growth rate and reduced susceptibility to predation (because of shorter presence in the water column) in the northern GSL, SS and off Newfoundland. Recruitment should improve in southern Labrador. The negative aspects of temperature may be enhanced, and the positive effects of temperature may be partly countered, by a negative impact of acidification on larvae (slower growth rates). There is little risk of mismatch between larval emergence and prey abundance for coastal lobster, because gonadal development is mostly under the influence of the same water masses where the larvae will feed. This may not be true of deep-water lobster living at the slope edge in the southern part of the distribution.

American lobster juveniles and adults prefer shallower coastal waters with rocks or vegetation for hiding, at depths 50-200 m. Temperature is the main determinant of distribution, not depth. Considering that T_{pII} is about 20 °C, projected changes in near-surface temperature will cause lobster from populations south of the Atlantic LAB, but also probably populations from the GM and southern GSL to become less abundant and restricted to deeper, colder water, and at the same time increase the prevalence of disease in these populations. Other populations should benefit from increased productivity. The distribution of American lobster may extend further north on the Labrador shelf. Lobsters in deeper waters (175-200 m) may experience hypoxic conditions that may slow development and reproductive potential, therefore lowering numbers.

4.4.2 Northern Shrimp

4.4.2.1 Background

The northern shrimp, *Pandalus borealis*, is a discontinuous circumboreal species (Allen, 1959; Shumway et al., 1985; Garcia, 2007), although Squires (1992) and Bergström (2000) argue that the Pacific populations form a different species, *P. eous*. Some of the data on tolerance to temperature and salinity are from Pacific *P. borealis/eous*, but are likely to apply to Atlantic populations as well, considering the similarity between these populations that can be inferred from the taxonomic debate about them. In the western Atlantic, P. borealis is found from Cape Cod to Baffin Island (Garcia, 2007). It is an important commercial species, ranging first in landings and third in value among shellfish in the Atlantic LAB, where it is widespread except for the southern GSL (Chabot et al., 2007), where bottom waters are very cold, and the central part of the Scotian shelf, which is generally too warm to constitute a good habitat for this species (Koeller, 2000). The eastern SS offers better (cooler) temperature conditions but muddy bottoms are rare, so that small populations are found in SS-GM (Koeller, 2000). It is a protandrous hermaphrodite species (born male, reproducing once or twice and becoming female) and the fishery targets females, because they are larger. Northern shrimp rank first in landings and 3rd in value among shellfish caught in the Atlantic LAB.

The northern shrimp is an important prey item for most commercial species of fish (cod, Greenland halibut, redfish, Atlantic halibut, herring) (Lilly et al., 2000; Savenkoff et al., 2006a; Savenkoff et al., 2006b; Savenkoff et al., 2006a; Savenkoff et al., 2006b; Dwyer et al., 2010; Dawe et al., 2012; Bernier and Chabot, 2013) and harp seals (Lawson and Stenson, 1997).

Spawning occurs in late summer or early fall in most areas (Ouellet et al., 2007; Koeller et al., 2009). Berried females carry their fertilised eggs on their pleopods until spring and typically migrate to shallower depths when the eggs are ready to hatch (Shumway et al., 1985; Apollonio et al., 1986). The newly-hatched larvae migrate to the surface layer (5–60 m, often within the top 30 m, Haynes, 1983; Shumway et al., 1985; Ouellet and Lefaivre, 1994; Bergström, 2000) and moult 5 times (five zoal stages and one megalopa, Rasmussen and Aschan, 2011) over a period of 2–4 months, depending on temperature (Shumway et al., 1985; Ouellet et al., 2007).

The megalopa become benthic and moult into juvenile shrimp, which are segregated from the adults, generally occupying shallower waters than the latter (Shumway et al., 1985). Adults can be found from about 9 m down to 1450 m over their range, although females are usually fished within 50–500 m on muddy-silty bottoms (Shumway et al., 1985). Adult shrimp, except berried females, perform diel vertical migrations, ascending in the water column in the evening and returning to the bottom in the morning (Shumway et al., 1985; Apollonio et al., 1986).

4.4.2.2 Temperature

From Cape Cod to Davis Strait, longevity, age and size at sex change and maximum size of males and females increase with latitude, while growth rate decreases (Shumway et al., 1985; Garcia, 2007). Considering the large range in surface as well as in bottom temperature over this wide region, these changes are likely due to temperature. Therefore warming could impact upon most aspects of the life cycle of shrimp.

Adults are found from -1.6 to ~12 °C (Allen, 1959; Shumway et al., 1985), although prolonged exposure to temperatures < -1 °C causes mortality (Bergström, 2000). Within this range, northern shrimp are usually found between 0 and 5 °C (Shumway et al., 1985) or -1 and 8 °C (Garcia, 2007) and can reproduce down to -1 °C (Garcia, 2007) and up to 11 °C (Allen, 1959). The ontogenic migration (e.g., juveniles occupying shallower water than adults, Shumway et al., 1985; Simard and Savard, 1990) has been interpreted as a sign that juveniles have a broader temperature and salinity range than adults (Garcia, 2007).

The growth rate of juvenile, male and female northern shrimp increases with temperature in the 2–8 °C range (Daoud et al., 2010). Moult increment is insensitive to temperature, but moult frequency increases with temperature. Juveniles are particularly sensitive to temperature changes. Oxygen consumption (both SMR and MMR) of juvenile and adult northern shrimp increases with temperature in the range of 2–8 °C (Daoud et al., 2007). Increasing temperature causes an increase in energy demand and growth rate will increase only if shrimp have an adequate food supply.

The duration of oogenesis as well as embryonic development are inversely proportional to bottom temperature within the range 2 to 9.5 °C (Shumway et al., 1985; Bergström, 2000; Arnberg et al., 2012). At 8–9.5 °C, hatching is more synchronous (shorter duration), although hatching success is lower (Nunes and Nishiyama, 1984; Brillon et al., 2005; Arnberg et al., 2012). In the GM, bottom temperatures > 5.5 °C result in higher egg morbidity because of the increased incidence of egg parasites (Apollonio et al., 1986).

Larval growth rate and energy requirements increase with temperature between 2 and about 8–10 °C (Shumway et al., 1985; Chabot and Ouellet, 2005; Ouellet and Chabot, 2005; Arnberg et al., 2012), at the cost of a lower survival rate at high temperatures (Nunes and Nishiyama, 1984; Arnberg et al., 2012), with possibly an optimum (compromise between development rate and mortality) at 9 °C (Bergström, 2000). The findings of Paul and Nunes (1983) agree with this suggestion: oxygen consumption peaks at 9 °C and the larvae appear to be under respiratory stress above 9 °C in zoea I. Experiments using a constant temperature for all larval stages are not realistic, however, because in the field, larvae experience warmer temperatures as they grow and it is likely that T_{pII} increases with age. Optimal conditions (compromise between growth rate and survival) may be cool temperatures (~3 °C) at time of hatching and a steady rate of warming during larval development (to ~6 °C) (Nunes and Nishiyama, 1984; Rasmussen and Tande, 1995).

About 45% of stage I and III larvae die at 16 °C (22 hour exposure) if they are acclimated to 4 °C (Stickney and Perkins, 1980, cited in Shumway et al., 1985), but this is unrealistic situation in the field (too large a sudden temperature change). With 10 °C acclimated larvae, the mortality rate is only 11.5 and 23% at 16 and 18 °C. As metabolic and feeding rates increase with temperature (Paul and Nunes, 1983; Shumway et al., 1985; Chabot and Ouellet, 2005), an appropriate supply of prey is required for larvae to survive in such warm water.

4.4.2.3 Dissolved oxygen

Dupont-Prinet et al. (2013a) have studied hypoxia tolerance of northern shrimp. Males are more tolerant to hypoxia than females: their O_{2crit} is lower (9.0 vs 15.5% sat., respectively, at 5 °C). For both sexes, O_{2crit} is greater at 8 than at 5 °C (13.8 and 22.3% sat. for males and females, respectively), a normal finding because of the increased metabolic rate and lower oxygen solubility at 8 °C. The AS of females was ~40% of normoxic AS in the range 22–35% sat., showing that this species is able to cope with severe hypoxia.

4.4.2.4 pH

Lowering pH from 8.1 to 7.6 slowed down development time in northern shrimp larvae, but only at 6.7 °C, not at 9.5 °C (Arnberg et al., 2012). A delay in development was also observed with pH 7.6 at 5 °C (Bechmann et al., 2011). Arnberg et al. (2012) concluded that the impact of climate change on northern shrimp larvae will be mostly due to temperature, not acidification. This conclusion may not be valid in the Atlantic LAB, where the first few larval stages are likely to be exposed to temperatures colder than 9.5 °C in 2060–2070 or even 2100, and may suffer a reduction in development rate due to acidification. This slower development rate may have a double impact if it prevents the larvae from reaching the megalopa stage before SST becomes very warm in July and August.

There are no data on the effects of acidification on the benthic phase of *P. borealis*, but the GSL shrimp populations have been abundant during the past 10 years, yet pH in the deep, hypoxic channels has been ~7.8 in Cabot Strait, decreasing to 7.6–7.64 in the Estuary (Mucci et al., 2011). However, the high abundance levels observed in recent years may be the result of predation release (Worm and Myers, 2003; Dawe et al., 2012), and therefore may not be a demonstration of the absence of negative impact of low pH. This needs to be investigated, as well as the impact of even lower pH, which should accompany the increase in bottom temperature and severity of hypoxia expected in 2060–2070.

4.4.2.5 Salinity

At 8 °C, northern shrimp larvae can handle salinity level down to 23.5 (the lowest tested), and mortality rate increased only for the less saline treatment. At 4 °C, however, mortality was high at salinities of 27.5, 26 and 23.5 (Shumway et al., 1985). Growth rate declines slightly below 28, and more rapidly below 25 (Wienberg 1982, cited in Bergström, 2000).

Juveniles can withstand a wider range of salinity than adults (Garcia, 2007), which are stenohaline and require high salinity (Allen, 1959; Bergström, 2000). Salinity preferences appear to range from, but in some cases shrimp have been shown to tolerate much lower salinity levels (as low as 23.4, for a review, see Shumway et al., 1985). In captivity at the Maurice Lamontagne Institute, adults are kept at salinities usually ranging from 27 to 29. Occasional drops in salinity below 26 increase the mortality rate (D. Chabot, unpublished data).

4.4.2.6 Conclusions

Optimal conditions for larvae appear to be cool conditions at time of hatching (SST of ~3 °C) and a warming of 2–3 °C during larval development. Warmer temperatures increase larval growth but decrease survival. A faster development time may reduce predation, however. Larvae can survive temperatures as high as 18 °C if acclimated slowly. Larvae have a wide thermal tolerance. It is impossible to make precise forecast of recruitment as a function of temperature.

Adult shrimp also have a wide thermal tolerance (-1.6 to 12 °C) and can reproduce over almost this entire interval. Growth rate increases with temperature, at least up to 8–9.5 °C (warmer temperatures have not been tested) and both oogenesis and embryonic development accelerates also within this temperature range. However, bottom temperatures > ~5 °C can reduce hatching success.

Because of hypoxia in the deep channels of the GSL, female shrimp have a limited AS there at present, especially at the head of the channels where hypoxia is most severe. This lower AS is not limiting at present (Dupont-Prinet et al., 2013a) and the head of the Anticosti and Esquiman Channels, and also the western part of the northern GSL, are heavily utilized by adult shrimp at present (Savard and Bourdages, 2012). A further decrease in DO levels in the Estuary and GSL, especially if accompanied by an increase in temperature (increasing energy requirements), could have very severe repercussions on the distribution and abundance of these populations.

There is a high risk of mismatch between hatching and algal bloom for this species. Hatching date is controlled by bottom temperature and date of egg extrusion (spawning). Koeller et al. (2009) found that hatching date in the spring coincides with the occurrence of algal bloom in most populations. Shrimp populations have therefore adapted to local conditions by adjusting spawning date to the expected rate of embryonic development. There is a risk of mismatch because of the projected differences in the rate of change in bottom and surface temperatures during the next 50–60 years (Chabot and Gilbert, 2013; Loder et al., 2013). Hatching date may become uncoupled from algal bloom.

In the past, the populations at the southern limit of the distribution (GM) fared better in terms of landings and recruitment during cooler periods (Koeller, 2000), and adults were found in the coolest part of the region during warm periods (Apollonio et al., 1986; Clark et al., 2000). These populations may not persist with a further increase of surface and bottom temperatures.

4.4.2.7 Synopsis for 2020-2030

Projected increase in SST variability should increase the frequency of good recruitment years in the GSL and NLSS because SSTs are presently colder than optimal temperature for larval growth. For SS-GM, the increased frequency of warm springs will likely reduce larval survival and increase the frequency of poor recruitment years and reduce shrimp abundance.

Projected small increase in bottom temperature will increase growth rate and productivity of benthic stages in GSL and NLSS, but on SS-GM, egg size may decrease and incidence of egg parasitism may increase. There will be increased risk of mismatch between larval emergence and spring algal bloom in this region. DO levels in the GSL will not change enough to influence this hypoxia-tolerant species.

4.4.2.8 Synopsis for 2060-2070

Projected increase in SST will favour larval development and survival in cold water stocks (NLSS). It is not clear if the changes in SST will benefit GSL larvae as late larval stages may face very high SST. However, hatching should occur earlier, and development rate be faster, because of the warmer temperature and earlier spring conditions. The megalopa are likely to reach cooler, deeper water before SST becomes too high. The overall effect would be positive. Recruitment will be consistently poor in SS-GM because of small larval size (see below) and high temperature-induced mortality rates of larvae.

There is a high risk of mismatch between larval hatching time and timing of algal bloom (and food abundance) in this species. The local adaptation of spawning date to local climate may be lost, considering that the rate of embryonic development is controlled by bottom temperature whereas the timing of spring algal bloom is controlled by surface temperature, and bottom temperature is projected to change less and more slowly than SST. This risk is highest in GSL and SS-GM, where temperature changes should be most pronounced. This could be made worse by the increased energy requirements of larvae exposed to high temperatures.

Projected increase in bottom temperature and projected decrease in CIL core temperature and CIL thickness will make habitat for juvenile and adult shrimp warmer than optimal temperature for growth and survival for populations influenced by slope water (SS-GM, GSL, southern part of Grand Bank). This would be made worse by hypoxia in the GSL: the head of the deep channels may become inhospitable to female shrimp, which are more hypoxia sensitive than males, if temperature increases by 1–2 °C and DO decreases by even a few % sat., as present levels are already close to the O_{2crit} of females. In the SS-GM, shrimp are likely to be economically extinct by 2060–2070, because of reduced recruitment due to reduced egg size, increased egg morbidity, increased larval mortality. There will be habitat loss where bottom temperature is > 12 °C.

Temperature in and below the CIL may increase growth rate of juvenile and adult shrimp for populations not exposed to slope water (NLSS). All populations may suffer from higher predation rates if cod populations rebound.

4.4.3. Snow Crab

4.4.3.1 Background

Snow crab, *Chionoecetes opilio*, is an arctic-boreal species, present both in the north Pacific and north Atlantic, but absent in the Arctic (Sainte-Marie et al., 2005). It is mostly found on shelves and slopes (Sainte-Marie et al., 2008) that are in contact with the CIL (Sainte-Marie et al., 2005). Snow crab is a very important commercial species, ranking second in landings and value among shellfish in the Atlantic LAB. The southerly distribution limit is on the eastern SS. Only males ≥ 95 mm carapace width (CW) can be landed.

It is a large species with pronounced sexual dimorphism: adult males are much larger than adult females. Large males can reach 162 mm in carapace width (Fonseca et al., 2008) or > 700 mm maximum span (Chabot and Claireaux, 2008), whereas adult females rarely grow larger than 70 mm CW (Alunno-Bruscia and Sainte-Marie, 1998). Snow crabs have a complex life cycle. There are two pelagic zoeal stages and one megalopa stage, which settles on the seafloor to moult into the first benthic instar (Davidson and Chin, 1991; Kon et al., 2003). Males can typically have 14 instars in the GSL (Sainte-Marie et al., 1995). Both sexes go through a terminal moult. In the Atlantic LAB, male typically become adult at 10.7 years or more after settlement on the bottom (Sainte-Marie et al., 1995). Male crab can live a maximum of 7–8 years after the terminal moult (Fonseca et al., 2008).

The most common items in stomachs of benthic snow crab are plant matter, molluscs, annelids, crustaceans (including northern shrimp and snow crab), echinoderms and fish (Wieczorek and Hooper, 1995; Lovrich and Sainte-Marie, 1997). Larger crabs eat larger prey and more fish. As a large and abundant predator, snow crab is thought to be an important species shaping the abundance of many of its prey species. Snow crab is preyed upon by Atlantic cod and thorny skates, but very rarely by Greenland halibut (Waiwood and Majkowski, 1984; Robichaud et al., 1991; Chabot et al., 2008; Dawe et al., 2012). Only snow crab < 65 mm CW are typically seen in fish stomachs, probably because maximum span exceeds the predators' mouth gap (Chabot et al., 2008). Fish can eat larger snow crabs for a short while after moulting, when in soft-shell (Robichaud et al., 1991).

4.4.3.2 Temperature

Snow crab is a cold-adapted stenothermic species. Juveniles and adults are found at temperatures ranging from -1.8 to 6 °C, although long-term survival is compromised below -1 °C and above 4 °C (for a review, see Sainte-Marie et al., 2005). Large males are sometimes observed at 7 °C in the GSL. Laboratory experiments showed them to be in a negative energy balance above 7 °C (Foyle et al., 1989). This suggests that T_{pII} and maybe also T_{cII}, is below 7 °C in large males. Another study suggests a higher T_{cII}: the median lethal temperature of adult males is 12 °C for 96 hour exposures (Hardy et al., 1994).

The first few benthic stages (instars I–IV) are even more stenothermic than the older instars. Snow crab are closely associated with the CIL, but avoid temperatures < 0 °C (Dionne et al., 2003). They are also found where bottom temperature is stable year round and avoid areas that are only cold in winter (shallow areas above the CIL). In the laboratory, instar III crab select temperatures of 0–1.5 °C when offered a choice, whereas instar V crab prefer a range of 1–4.5 °C (Dionne et al., 2003). Temperature appears to be more important than substratum or depth to explain young juveniles' distribution (Brêthes et al., 1987; Dionne et al., 2003).

Within the acceptable range, warmer temperatures result in larger adults of both sexes. The mechanism appears to be the decreased intermoult interval with increasing temperature, allowing crab to reach one or more additional instar in warm water (3 °C) than in cold (0 °C) water (Sainte-Marie et al., 2008; Burmeister and Sainte-Marie, 2010; Dawe et al., 2012).

In the GSL, and probably in the rest of the Atlantic LAB also, hatching takes place from April to June (Davidson and Chin, 1991; Sainte-Marie, 1993; Starr et al., 1994; Conan et al., 1996), peaking in May (Lanteigne, 1985). In the Sea of Japan, snow crab larvae (2 zoeal stages) are found in greatest numbers at temperatures varying between 8 and 15 °C (Kon et al., 2003). Snow crab larvae die before reaching the megalopa stage if temperatures are > 15 °C (Kon, 1980; Lim et al., 2001). Larval development rate increases with temperature. The zoea I intermoult interval is 57 d at 5 °C, but only 23 d at 15 °C, and that of the zoea II is 52 d at 5 °C and 19 d at 15 °C, with intermediate values and best survival at 10 °C (Lim et al., 2001). The megalopa stage lasts approximately 2 months at 12 °C (Kon et al., 2003), although Davidson and Chin (Davidson and Chin, 1991) obtained 33 d at 11 °C in captivity, but for a single individual. The survival of the zoea I is reduced below 5 °C or above 10 °C, whereas that of the megalopa is reduced below ~10 °C (Kon, 1980; Davidson and Chin, 1991; Kogane et al., 2005). In the GSL, zoea are associated with waters < 5 °C soon after hatching, and warmer waters (10–15 °C) in late July and August. In the southern GSL, where surface waters are relatively warm in spring and summer, larval development takes ~3 months, and approximately one month for the megalopa (Lanteigne, 1985).

Zoea II and megalopa perform diel vertical migrations, and can adjust their vertical position (Kon et al., 2003), presumably to select the best available temperature or prey availability. Megalopa start diving into the cold bottom water when they reach the premoult stage (Kon et al., 2003). In the southern GSL, they settle on the bottom from late August to September-October (Lanteigne, 1985; Robichaud et al., 1989; Lovrich et al., 1995) and probably later in the eastern part of the GSL and in NLSS.

Females reproduce every two years in cold waters (< 1 °C, typical of the southern GSL), and yearly if temperature is > 1.8 °C (Moriyasu and Lanteigne, 1998). Sainte-Marie et al. (2008) estimated the temperature where this switch occurs to be ~0.75 °C. Thus a small warming could increase reproductive output in areas where bottom temperature is currently < ~0.75 °C, because of a doubling of spawning frequency and a large size at adulthood (and thus greater fecundity) in females (Sainte-Marie et al., 2008).

4.4.3.3 Dissolved oxygen

In a study on thermal preference of early benthic stages of snow crab, Dionne et al. (2003) observed that snow crab lost equilibrium when DO dropped to below 70% sat. The authors suggested that DO, along with temperature, may be defining the observed maximum depth of juvenile snow crab distribution in the GSL. It is likely that another factor than oxygen caused this behaviour change in the experiment of Dionne et al. (2003), because preliminary experiments conducted at the Maurice-Lamontagne Institute showed benthic snow crab from early instars to adults to be very hypoxia tolerant, with no significant mortality down to below 30% sat. (D. Chabot, Maurice-Lamontagne Institute, unpublished data).

Adult male snow crabs are frequently encountered in the Laurentian and Esquiman Channel at DO levels ranging from 18 to 30% sat. (Sainte-Marie et al., 2005). Further evidence of hypoxia tolerance comes from the fact that the closely related *C. tanneri* is the dominant decapod crab on the floor of the Montery Canyon, at 1000 m, where DO levels are ~10% sat. (Pane and Barry, 2007). There are reasons to believe that *C. opilio* is not as tolerant as *C. tanneri*. Firstly, McLeese and Watson (1968b) found the O_{2crit} of adult snow crab at 5 °C to be ~27% sat. Secondly, preliminary results from experiments at the Maurice-Lamontagne Institute suggest that although immature and adult snow crab can survive several weeks at DO levels ranging from 12 to 20% sat., their behaviour is disrupted: locomotor and feeding activity absent (D. Chabot, Maurice-Lamontagne Institute, unpublished data).

4.4.3.4 pH

There are no data on pH tolerance in snow crab. The closely related C. tanneri is capable of very limited acid-base regulation when exposed for 24 h to a pH of 7.1, and is not able to regulate extracellular pH at all if acidification is accompanied by hypoxia (10% sat.) (Pane and Barry, 2007).

4.4.3.5 Salinity

Chionoecetes crab are not osmo-regulators, which is not a problem for the benthic stages, who live in a very stable environment with high salinity (for reviews, see Hardy et al., 1994; Charmantier and Charmantier-Daures, 1995). Zoea I can tolerate short exposures to salinities as low as 10 units: the median lethal levels are 10, 18 and 25 units after 24, 48 and 96 hours of exposure. Thus, larvae can tolerate low salinity levels but for a short duration. The median lethal salinity (96 h) of benthic snow crab is 13.5 at 6 °C (Charmantier and Charmantier-Daures, 1995). Similarly, estimated survival time is shorter than 96 hours when salinity falls below 22 units (Hardy et al., 1994).

4.4.3.6 Conclusions

As the habitat of the benthic phase is restricted to temperatures ranging from -1 to 3 °C year-round, snow crab is restricted to parts of the Atlantic LAB where the bottom is in contact with the CIL. Further, as many aspects of these crab's physiology (growth rate, final size, fecundity, reproductive frequency) can change dramatically with small changes in temperature, this stenothermic species is highly vulnerable to climate change. As the CIL is projected to be both warmer and thinner, the surface area of the bottom in contact with waters colder than 3–4 °C will be less than at present, reducing the potential habitat of snow crab on eastern SS but also in the GSL and NLSS. A shrinking (or possibly disappearance) of bottom area in contact with very cold (< 0.75 °C) water will have one benefit: females in these areas will switch to reproducing yearly. Because of warmer temperatures, a larger proportion of the snow crab distribution is likely to overlap with predators such as cod, which have been shown to have an impact on snow crab distribution in the east Bering Sea (Orensanz et al., 2004). Cod likely influenced recruitment strength in the Atlantic LAB in the past (for a review, see Chabot et al., 2008; for an opposing point of view, see Boudreau et al., 2011).

In a comparison of three snow crab populations (eastern Bering Sea, Newfoundland-Labrador shelf, southern GSL), Marcello et al. (2012) found that cold conditions for the first few benthic stages result in good recruitment. For the southern GSL population, cold conditions were quantified as the extent (km^2) of the bottom with temperature < 3 °C in September. For NLSS, it was the annual ice cover area. By both measures, the frequency of good recruitment years is expected to decrease by 2020–2030. Good recruitment is likely to be rare by 2060–2070 except in NLSS.

Snow crab is known to respond to temperature changes by contracting or extending their distribution. On the eastern SS, the area where snow crab can be fished matches the distribution of cold water in summer (Tremblay, 1997). As a consequence of warming, snow crab populations in the North Pacific have contracted northward (Orensanz et al., 2004) and now extend into the Beaufort Sea (Rand and Logerwell, 2011).

Indirect effects of climate are likely for this species. In the East Bering Sea, strong vertical mixing and an unstable water column inhibits growth of diatoms that provide high-quality nutrition to early zoeal crab larvae (Zheng and Kruse, 2000). Because the benthic phases of snow crab are restricted to such a narrow temperature range, the rate of embryonic development is not expected to change much by 2020–2030 or 2060–2070. However, surface waters are expected to become warmer and spring algal blooms should occur earlier, possibly causing a mismatch between crab larvae and their food supply. Until recently, there appeared to be a mechanism to prevent such a mismatch: Starr et al. (1994) concluded that hatching was triggered by chemical cues from decaying phytoplankton sinking to the seafloor, tying newly hatched larvae to an ample food supply. However, a recent study was not able to corroborate this result and concluded that hatching was under endogenous control (Kuhn et al., 2011). Therefore, the possibility that young crab larvae will miss the pulse of plankton production does exist.

4.4.3.7 Synopsis for 2020-2030

Optimal temperature for larvae is 8 to 15 °C. Temperatures greater than 15 °C are lethal. August temperature in the southern GSL, along the west coast of NF and on the ESS averages about 15 °C at present. The projected small increase in SST and increased frequency of warm SST years, and the freshening of the surface layer in the St. Lawrence Estuary are unlikely to impact zoea. Increased temperature will allow them to complete the pelagic phase sooner. Further, larvae are able to adjust their vertical distribution and select favourable conditions, as long as prey will remain abundant at the depth selected by the crab larvae. Megalopa are distributed at greater depths than zoea and will not be impacted upon by warm SST, adjusting their depth if need be. More frequent warmer summer should be beneficial in the colder areas, where present temperatures in late summer are below the most favourable temperatures for larval development.

The optimal habitat of benthic snow crab (juveniles and adults) is soft bottom at temperatures between 0 and 2 °C for juveniles < 12 mm CL and between -1 to 4 °C for older crabs. Projected small decrease in CIL thickness and increase in core temperature, and increased variability in same parameters, could increase mortality in early snow crab settlers, which are sedentary and cannot seek better conditions if their habitat warms up from one year to the next. Projected increased temperature in CIL and frequency of warm years may result in an increase in growth rate and maximum size of males, and in a decrease of the frequency of 2-year reproduction cycles in females. Both would be beneficial until continued warming shrinks available habitat.

4.4.3.8 Synopsis for 2060-2070

The optimal temperature for larvae is 8 to 15 °C. Temperatures greater than 15 °C are lethal. August temperature in the southern GSL, along the west coast of NF and on the ESS averages about 15 °C at present. Snow crab zoeae are able to adjust their vertical distribution and select favourable conditions, but it is not known if feeding conditions will be adequate at the depths that will be selected to counteract the projected warmer SSTs. Megalopa are thought to be more epipelagic and are unlikely to be negatively affected by the warm SSTs that are expected to characterize late summer and early autumn. The overall effect could be favourable, regions that have cold SSTs in early summer and August at present could offer conditions closer to the optimal for zoeae and megalopa. However it is not known if hatching time will change to track earlier projected plankton blooms, or if food will be abundant at the depths selected by larvae. Larval growth and survival would decline if there were a spatial (depth) or temporal mismatch with food supply. Hypoxia is not a problem at the depths exploited by snow crab larvae.

The optimal habitat of juvenile and adult snow crab is soft bottom at temperatures between 0 and 2 °C for juveniles < 12 mm CW and between -1 to 4 °C for older crabs. Projected decrease in CIL thickness and increase in core temperature (1–2 °C) will have a major effect on this stenothermic species. The distribution will shrink considerably, with commercial extinction likely on the SS and southern NF, and possible for other populations as well, such as the St. Lawrence Estuary, where adequate bottom temperatures will be limited to narrow bands. If recruitment (megalopa supply) remains strong, mortality through cannibalism could increase on the much more limited available habitat. The relative impact of predation by demersal fish such as cod could be enhanced because warming is expected to be generally favourable to cod, and the overlap between cod and juvenile or moulting legal-size snow crab will increase as a result of the increased in CIL temperature and possible earlier migration of cod to spawning and feeding grounds. Thus cannibalism and predation could reduce snow crab abundance on remaining available bottoms. These negative impacts will be in part compensated by increases in growth rate and maximum size of males, and increased frequency of annual reproduction cycle in females. However the increase in final size of males will result in a greater proportion of males reaching commercial size and management policies will have to be adapted to maintain the remaining stocks' reproductive capacity. Large males may no longer enter hypoxic zones because of the expected warmer bottom temperatures and worsening of hypoxia projected for the deep channels of the GSL. Snow crab could extend its range northward along the coast of Labrador, although currents would not be favourable to larval drift towards the new areas, and colonization may require migrations of adult snow crab.

4.5. DISCUSSION

The aim of this chapter was to assess the likely impact of the changes in physical characteristics (temperature, dissolved oxygen, pH and salinity) projected to occur in the Atlantic LAB on the physiology, and by extension, the productivity and distribution of a subset of exploited marine fish and crustaceans. General principles on how these environmental variables control limit physiology (Chabot and Guénette, 2013) were used to determine if changes in distribution or productivity were likely for two time periods, 2020–2030 and 2060–2070. The species selected include all major marine fish and crustaceans exploited in the Atlantic LAB. The synopses for each species (one for each time period) are presented after each species' review. The synopses were then used to prepare the risk assessments required by the Department of Fisheries and Oceans.

Generally speaking, our findings agree well with those of studies and models dealing with climate change. First, clearly, temperature is a major determinant of marine species distribution. Current fish distributions are the expression of their thermal tolerances (Pörtner and Farrell, 2008). The geographical limits are defined by occasional thermal extremes or shock occurring in winter in the northern part of the distribution, and in the summer in the southern part of the distribution (Pörtner and Peck, 2010). As water temperature increases, fish are expected to move their center of distribution to continue living within their preferred temperature range. In the northern part of the distribution, growth and fecundity are expected to increase as a consequence of changes in energy budgets (Pörtner, 2001). Other factors such as hypoxia, and loss of habitat could contribute to changes in distribution but current studies mainly address the effect of temperature as the major factor in determining species distribution. Global warming and its associated effects on level of CO_2, acidification, salinity, ice, oxygen saturation level will have direct effects on the physiology and distribution of marine species. Changes in distribution and production will be governed by average environmental conditions but also by the occurrence and extent of extreme conditions, especially at critical times of the species life history (spawning, migrations, larvae and juvenile growth). Finally, northward range extensions require that ocean circulation make it possible for eggs and larvae to drift northward, or that adult fish move northward. In the Atlantic LAB, currents are generally southward at all depths along the Labrador coast and species which rely on larval dispersion to colonize new habitats will have difficulty in exploiting new habitats made available by warming. The haddock and the snow crab are examples of this.

The direct effects of climate change on marine fishes and crustaceans are physiological ones. But it is difficult to determine the impact of climate change on species based on physiology only. Our knowledge of the optimal and tolerable ranges of temperature, dissolved oxygen, pH and salinity goes from extensive in the case of cod, to limited in most other marine fishes and crustaceans. Even in the case of cod, by far the most studied of the species that we examined in terms of physiological tolerance, there are few studies combining multiple environmental variables. At the time of writing this review, the predicted changes in environmental variables for the two periods, 2020–2030 and 2060–2070, were general and involved fairly wide ranges. Further, changes projected for the period 2020–2030 are expected to be within the range of natural variability at present, and possibly by an increase of what constitute extreme events at present (Loder et al., 2013). The most likely effect of this scenario is an increase in recruitment variability, as indicated in the synopses for that time period. More important changes, especially in temperature, DO and acidification, are projected for the period 2060–2070. Most species examined will be impacted upon by such environmental changes. Table 4–1 summarizes qualitatively the synopses found in the main body of this chapter.

Our analysis, based only on what is known of the physiological tolerances of these species to temperature, DO and acidification, indicates that no positive but many negative impacts are expected in SS-GM, a mixture of negative and positive impacts are expected in the GSL, and mostly positive impacts are expected for NLSS (Table 4–1). These findings result from the fact that SS-GM is near or at the southern edge of the distribution for most of the species examined, and therefore are probably exposed at present to the warmest temperatures they can tolerate. The opposite is true in NLSS, which is the center of distribution, or in some case the northern edge of the distribution, for these commercial species. In addition, warming is not expected to be as pronounced in NLSS than for the rest of the Atlantic LAB (Loder et al., 2013).

In the northern hemisphere, the more visible aspect of distribution change is a true northward extension of both the north and south limits of the existing distribution range of a species. Several studies have reported massive displacement of fish populations towards the poles and deeper waters (Drinkwater, 2005; Perry et al., 2005; Simpson et al., 2011). Most of the species that we examined cannot compensate habitat loss at the south of the Atlantic LAB with an extension in the north because they already occupy the northern part of the LAB. Extensions further north would not benefit the fishing industry in the Atlantic LAB.

Any shift in latitude is minor compared to the potentially profound changes in the relative abundance of species: shifts in distribution also result in the increasing abundance of warm water species accompanied by the declining abundance of cold water species in regions that were already part of the distribution of these species. For instance, it is not known what impacts an increase in lobster, mackerel and haddock could have on the species already important in NLSS.

Fishing can decrease species resilience to environmental change. For instance, the cold period of the late 1980s and early 1990s on the east coast of Canada resulted in important changes in production and distribution for numerous marine species, including many fished species, from which the ecosystem has not recovered. Management of these species will have to be adjusted for the changes in productivity caused by warming, such as the change in the proportion of males reaching commercial size in snow crab.

Table 4–1 Qualitative summary of the expected impacts in 2060–2070 of climate warming on recruitment (R), distribution (D) and productivity (P) of some important commercial species of demersal and pelagic fishes and crustaceans in the three sub-basins of the Atlantic Large Aquatic Basin. Impacts can be strongly negative (--), negative (-), neutral or indeterminate or a mixture of positive and negative impacts in different zones (.), positive (+) or strongly positive (++). Positive effects will require an appropriate food supply to fuel the faster metabolic rate of aquatic breathers in warmer water. Positive effects on recruitment will be negated if climate warming results in mismatch of larval emergence and planktonic blooms.

Species	Ranking (landings)	Ranking ($ value)		Scotian Shelf and Slope, Gulf of Maine (SS-GM)	Gulf of St. Lawrence (GSL)	Newfoundland and Labrador Shelf/Slope (NLSS)
Demersal fishes						
American plaice	6	7	R	-	.	.
			D	-	-	.
			P	.	+	+
Atlantic cod	4	4	R	.	+	+
			D	.	-	+
			P	.	+	+
Atlantic halibut	8	2	R	.	.	+
			D	-	.	+
			P	-	+	+
Greenland halibut	2	1	R	-	-	.
			D	-	--	.
			P	-	-	.
Haddock	1	3	R	.	+	+
			D	.	+	+
			P	.	+	+
Redfish	3	5	R	.	+	+
			D	-	.	.
			P	-	.	.
Pelagic fishes						
Atlantic herring	1	1	R	-	.	+
			D	-	.	+
			P	-	.	+
Atlantic mackerel	3	2	R	.	+	+
			D	.	.	+
			P	.	+	+
Capelin	2	5	R	-	-	.
			D	-	-	.
			P	-	-	.
Crustaceans						
American lobster	3	1	R	.	.	+
			D	.	.	+

Species	Ranking (landings)	Ranking ($ value)		Scotian Shelf and Slope, Gulf of Maine (SS-GM)	Gulf of St. Lawrence (GSL)	Newfoundland and Labrador Shelf/Slope (NLSS)
			P	.	.	+
Northern shrimp	1	3	R	-	.	+
			D	-	- -	.
			P	-	-	+
Snow crab	2	2	R	-	-	.
			D	-	-	-
			P	-	-	-

4.5.1 Limitations of the Study

4.5.1.1 Predicting the future physical properties of the Atlantic LAB

Predicting future climate is not an easy task. Many teams worldwide are modelling future climate, with diverging results and a fairly coarse grid. The Trends and Projections team compared the results of these models for the Atlantic LAB, and developed models on a finer grid. But the projections are still more imprecise than one would like to infer changes in species distribution and productivity (Chabot and Gilbert, 2013; Loder et al., 2013).

4.5.1.2 Simplifications

Global warming will impact species and their ecosystem through several additive pathways and mechanisms, from changes in primary production, differential changes in population production, phenology, and distribution, and trophic and non-trophic relationships, as well as fishing pressure. Commercially important species can be affected by directly by climate change, via changes to their physiology, but there are possible indirect impacts as well, through changes in the ecosystem and trophic linkages. The community of species that occur in an ecosystem co-exist because of their overlapping thermal (and DO, pH, salinity) windows. Since the degree of overlap is a function of species-specific physiology and resulting climate sensitivity, climate induced-change may result in changes in timing in the production of food and interactions with predators and competitors (Pecl and Jackson, 2008; Pörtner and Peck, 2010). In particular, the increased probability of mismatch between the larvae of several of the species reviewed here and the peak in abundance of their potential prey has been mentioned repeatedly. This risk cannot be evaluated with existing knowledge but has the potential to jeopardize recruitment. The impacts on adults would therefore be underestimated. Juvenile and adults may also have to deal with changing prey abundance, and possibly also with the disappearance of preferred prey species and the appearance of new potential prey. Feeding is a crucial aspect because warming will increase the metabolic rate and energy requirements (usually oxygen requirements also) at all trophic levels.

However, only direct effects of four environmental variables on the physiology of the selected species were considered. Further, a more complete analysis would have dealt with all life stages of a species. This was beyond the scope of this review, although we attempted to evaluate life stages that are likely to experience different changes in environmental parameters, such as pelagic larvae and benthic/demersal juvenile and adult stages. The inclusion of indirect (ecosystem) effects may have changed the details of our assessment for each species, but we think the synopses that we produced are fairly robust.

Time constraints also limited the number of species included in this study. The absence of molluscs, for instance, is a major limitation, considering their importance in the Atlantic LAB fisheries. Many molluscs are vulnerable to acidification (Chabot and Guénette, 2013). In addition, sessile invertebrates living in the intertidal zone face many challenges. They are at the limit of their thermal tolerance, especially in warmer sites. In response to observed warmer summer temperatures in British Columbia (3.4 °C increase over 52 years), the vertical distribution of mussels and barnacles has decreased, meaning that these species cannot live as high in the intertidal zone due to desiccation and thermal stress (Harley et al., 2006). On the other hand, the main mobile predators are not necessarily limited by temperature and continue to have access to their prey, which translates into a stable lower vertical limit, controlled by predation. Thus, a warmer intertidal zone would result in 1) restricted distribution for sessile prey, and disappearance from the most extreme sites; 2) a larger proportion of the population exposed to predation; 3) changes in biodiversity when the prey creates habitat for other species. For instance, mussels provide cooler habitats and shelter for an array of mesofaunal species that would be impacted by the disappearance of their host (Harley, 2011).

The differential effects of climate change on the species composing an ecosystem, and the arrival of southern species invading the Atlantic LAB will modify the functioning and production of the Atlantic LAB's ecosystems. Southern species, often smaller and with different phenology and life histories may not replace indigenous species as well if at all, and energy pathways may be changed. This has been shown for zooplankton and possible mismatch with cod larvae in the North Sea (Beaugrand et al., 2003). Different life histories and ecological preferences, such as found in complex interactions of fucus, limpet and barnacles also suggest that changes may be more profound than can be inferred from temperature changes alone (Hawkins et al., 2008).

4.5.2 Perspectives

4.5.2.1 The interaction between climate change and fishing

Observed changes in abundance and distribution in most oceans are marred with simultaneous influences of environmental conditions, fishing and other anthropogenic changes that are often difficult to disentangle.

Both climate and fishing affect species in a size specific way. Previous sections described how the effects of climate change vary with developmental stages and population life history characteristics. Fishing makes populations more vulnerable to extreme environmental conditions by modifying several aspects of the population dynamics. These are well documented and recently reviewed by Planque et al. (2010), and are only listed and described briefly here. Fishing truncates the age and size structure of a population. This influences reproductive capacity and ultimately recruitment. The impact is even more important on long-lived species that have evolved to sustain adverse environmental conditions with overlapping generations (Longhurst, 2002). Fishing can also remove genotypes and reduce a stock's capacity to respond to some stressors (Perry et al., 2010). Several studies suggest that migration is at least partly learned from older individuals and that a stock collapse coupled with the loss of older individuals could lead to loss of traditional migration destinations. It is often difficult to distinguish the effects of change in distribution following stock collapse and truncation of age structure.

Several studies aimed at delineating the effect of fishing and climate. For instance, ter Hofstede and Rijnsdorp (2011) compared four periods with different combinations of fishing pressure and temperature anomaly. Warm-water fish tended to be caught in larger numbers in warmer periods and more so in recent years, perhaps because of the continuous increase in temperature since the 1970s. In both warm water and cold water, maximum body size declined as fishing pressure increased.

Atlantic cod provides another example of the interaction between fishing and climate. As seen in the Atlantic cod section above, growth, condition and surplus production have been linked to temperature (Brander, 1995; Dutil and Brander, 2003; Lambert, 2011), and these stock properties are known to impact fecundity (Pörtner et al., 2001). When cold periods succeeded to warm periods, responses in distribution, growth, spawning time and recruitment have been observed (Drinkwater, 2005). Overfishing was the main factor explaining the collapse of the northern cod. Spawning biomass was low since the late 1960s and fishing mortality was very high, due to excessive targeted fishing and unreported discards and catches (Lilly, 2008). As a result, the population structure showed the classic signs of overfishing. For instance, in the early 1990s, the age and length structure were truncated and the catch was dominated by three age classes (4-6), compared with that of the 1960s that included cod of up to 20 years old (Lilly et al., 1999). In addition, the age and length at maturity declined (Trippel, 1995; Hutchings, 2005; Fudge and Rose, 2008).

From the late 1980s to 1993, the NAO index was strongly positive and the water temperature lowered. In response to strong negative temperature anomalies, growth and weight-at-age declined for northern cod (areas 2J3KL) (Drinkwater, 2002). Recruitment was linked to spawning stock biomass and perhaps to environmental factors such as temperature, although the relationship with the latter is equivocal (Drinkwater, 2002). Besides, fish condition and size structure have been shown to negatively affect realised fecundity (Hutchings and Myers, 1993; Marshall et al., 1998). Similarly, Lambert (2011) showed that in the northern GSL, cod experienced decreases in growth, size at age, condition, and reproductive potential in the late 1980s until 1993, when temperature anomalies were highly negative. Hence, the synergy between overfishing and the consequences of colder temperature resulted in the catastrophic decline of eastern Canadian cod in the early 1990s.

The changes in population dynamics resulting from colder temperatures were accompanied with changes in distribution. For instance, during the 1980s-1990s, cod from area 2J, the northern limit of the stock, exhibited a southward shift in distribution, accompanied with changes in schooling and wintering behaviour (Rose et al., 1994; Kulka et al., 1995; Atkinson et al., 1997). Other species also showed a shift in distribution (see review in Drinkwater, 2002), including capelin. Changes in distribution have also been shown for cod in the Barents Sea, Greenland and Iceland (Drinkwater, 2005).

Ecosystem-wide analysis including the effects of fishing, climate and predation, have shown that fisheries constitute the main factor of change in ecosystem structure, although not the only one. Colder temperatures were deemed responsible for the increased abundance of Arctic species and the decrease in productivity during the colder years in the southern GSL (Benoît and Swain, 2008). An analysis of 7 ecosystems of the western Atlantic (Canada and US) describes how the main effects on the biomass and body size of exploited species are more linked to fisheries than climate, and this could in turn result in trophic cascades (Shackell et al., 2012). The effect of climate indices seem to depend on the ecosystem concerned, that is, exacerbate the fishing impact in the north and mitigate it in the south.

Fishing and climate change can interact in surprising ways. For instance, climate change resulted in a distribution shift for plaice (*Pleuronectes platessa*) in the southern North Sea (Engelhard et al., 2011). Plaice moved to the north and west since the 1920s, and the species is now present in large numbers along the Scottish coast. Juveniles, and especially 1-year old plaice showed the same trends, accentuated in the 1990s (van Keeken et al., 2007). In all likelihood, more than one factor is responsible for this movement to deeper waters: maximum water temperature increasing over 20 °C and even reaching the critical limit of 24 °C which provokes mass exodus of 0+ plaice, changes in ecosystem structure with increase in cormorant predation in shallow water and a reduced predation by large plaice offshore (van Keeken et al., 2007). This shift in distribution resulted in juveniles deserting the “plaice box”, the previous nursery area that was closed to plaice fishing to prevent the bycatch of juveniles. The bycatch of juveniles outside the protected area increased. The plaice box is no longer fulfilling its role and will likely have to be modified to be more easily adapted to environmental changes. The authors mention that increasing temperature adds to the long list of anthropogenic influences on plaice and sole habitat, which also includes the closures of rivers and habitat degradation of nurseries that affect this population (Engelhard et al., 2011).

Only a few studies have attempted to address ecosystem-wide changes by considering a combination of climate, eutrophication, fishing, etc. For instance, the shift in ecosystem structure of the Baltic Sea from the period 1974-1987 to

1994-2005 likely resulted from hydro-climatic changes accompanied by an increase in temperature, decrease in oxygen level and salinity, the resulting shift in dominant copepods, and overfishing (Möllmann et al., 2008; Möllmann et al., 2009). In the Atlantic LAB, cod has not recovered in spite of improved environmental conditions. The authors emphasized the importance of maintaining the resilience of ecosystems by effectively controlling anthropogenic impacts.

4.5.2.2 Modelling approaches

Models have been used to explore possible effects of global warming concerning biodiversity, fisheries production and ecosystem functions using various approaches. They are also used to identify gaps in knowledge, possible mechanisms and potential sensitivities. Several models exploring the impact of climate change have been published and an exhaustive review falls outside the scope of this report. A few examples are provided below, with a focus on models used to explore the effects of global warming and on the benefits of each approach.

Individually Based Models (IBM) aim at understanding the mechanisms that would lead to change in population dynamics by keeping track of individuals or super-individuals through their passage in various life-stages, and migrations. This has been attempted in the case of capelin in the Barents Sea (Huse and Ellingsen, 2008). Outputs from biophysical models were coupled to empirical equations and detailed data describing traits of capelin life history to build a functioning model and investigate the effects of global warming on capelin distribution and population dynamics. The model predicted shifts in spawning locations, including new spawning sites (Huse and Ellingsen, 2008). However, assumptions about the link between marginal ice zones in the summer may or may not hold if the ice was to retreat too far in the Arctic; then capelin may rather feed in warmer waters and perhaps be subjected to higher predation from cod (Huse and Ellingsen, 2008).

Bioclimatic envelopes have been used to predict changes in distribution, mainly based on a set of physical and biological conditions, generally temperature, habitat preferences and sometimes time series of spatially-structured catch records. A bioclimatic model was built for 16 species of large pelagic fishes (tuna, marlin, large sharks, etc.) living around Australia (Hobday, 2010). Given the considerable uncertainty about the projections in CO_2 produced during the next century, results varied widely in the strength and sometimes in the direction of responses. Model predictions also varied depending on the region examined, predicted regional impacts of currents, and interactions with other factors. Nevertheless, results generally predicted a shift of distribution to higher latitudes and decrease in area of distribution because the availability of suitable area decreased by 2100. This would likely have implications for fishery management and the possible relocation of fishing ports. Rombouts et al. (2012) provide an example of a niche model for benthic invertebrates in the English Channel and the projected distributions based on temperature.

Bioclimatic envelopes are good first approximations, but their weakness is simplification, usually only considering temperature effects and no trophic interactions. Species responses to warming are also a function of their life histories and ecological traits, and of their trophic and non-trophic inter-specific interactions (Hawkins et al., 2008; Harley, 2011; Russell et al., 2012). In addition, species of similar functional groups are not necessarily interchangeable due to difference in behaviour and population dynamics (Hawkins et al., 2008). Species changes may results in strikingly different dynamics. Thus, more predictive models would need to include specific life history traits.

Cheung et al. (2009) developed a dynamic bioclimatic envelope model overlaying environmental data and habitat preferences coupled with a logistic growth model, larval dispersal and adult migration. Over a thousand pelagic and demersal species were modelled worldwide. The results suggested dramatic changes in distribution and turnover of 60% of the present biodiversity with climate change, implying serious ecological disturbances.

The model was later augmented with explicit considerations for change in species growth and production including temperature dependent metabolism, and decrease in AS as a response to changes in temperature, oxygen and acidification. The study covered 120 species of the Northeast Atlantic (Cheung et al., 2011). Various scenarios of biogeochemical and primary production scenarios were considered. The model predicted shifts in distribution towards the pole and deeper waters. Results show that when the model includes only the effect of species distribution and primary productivity, shift in distribution were estimated at 45.5 km per decade and catches were predicted to increase in northern regions (Greenland, Barents Sea) by 40 to more than 80% while that of the southern regions (e.g., Celtic-Biscay shelf, North Sea, Iberian coast) were predicted to increase only by less than 5% by 2050. After adding the negative effect of oxygen, pH and plankton size structure to the model, catches were predicted to increase by about 10 to 45% in the northern regions, but to decrease by about 20% in southern regions (Cheung et al., 2011). This model is interesting because it allows the exploration of the effect of uncertainties and the potential cumulative effects. However, it does not take trophic interactions into account. It includes the effect of phytoplankton production and size structure by directly making assumptions about the effect they have on trophic efficiency at various trophic levels (each species being characterized by its trophic level).

Ecosystem models were also used to account for species interactions when exploring the effects of climate. Ainsworth et al. (Ainsworth et al., 2011) used five Ecopath with Ecosim models of the Northeast Pacific and used functional relationships to include the effects of shifts in distribution, oxygen, acidity, primary production and size structure of zooplankton. The results suggested synergies between these sources of perturbations from global warming with predicted decrease of about 77-85% in catch and about 30% in total ecosystem biomass depending on the warming scenario and the ecosystem considered. Some groups were less affected or even benefited from the ecosystem changes as a result of modified trophic relationships. Nevertheless, it is acknowledged that several mechanisms and feedback effects were ignored or not well known, which may have influenced predictions.

Integrated Assessment Models (IAM) attempt to assess the impact of environmental changes on the economy, including impacts on fisheries. According to Fulton (2011), many suffer from simplifications of key components, such as temperature effects of aquatic animals. Worse, there is little or no consideration to other impacts of warming on fishes and invertebrates, such as increasing hypoxia or acidification. To alleviate these shortcomings, Fulton (2011) used a combination of end-to-end (or whole-of-system) models to examine the impacts of global warming on both ecosystems and fishing. The models were modified to include changes in a large variety of environmental factors: temperature, salinity, pH, and dissolved oxygen regimes (which in turn could drive shifts in species distributions), sea level, storm frequency and intensity, the entry or exit of species with shifting distributions, and the location and nature of major coastal industries and regulatory systems (Fulton, 2011). These models predict non-linear responses over time and very different responses among functional groups with pelagic species generally increasing while some demersal groups tend to decrease. Also, the rate of change in distribution was found to vary among species, which could lead to large-scale changes in ecosystem structure. The models predicted a decrease in estimated multispecies Mean Sustainable Yield (MSY) and differential effects on the fishing industry between small and large operators. Interestingly, the results were found to be quite consistent in terms of form and driving mechanisms across the model types.

4.5.3 What Should Be Done Next?

In the short term, curbing CO_2 emissions and the rate of deforestation is considered essential to decrease the rate of warming in the long term (Shackell and Loder, 2012). In parallel, fisheries and more largely natural resources (ecosystem-based) management will have to adapt to changes in distribution and productivity of exploited species, as well as to changes in fishing patterns as the fleet will also try to adapt.

An important tool for DFO to adapt to the changes anticipated in the Atlantic LAB ecosystem is to continue existing, and probably add new long-term and well-designed monitoring programs. These should be accompanied with a set of specific ecological studies on exploited species and emerging phenomena (field and lab work) designed to inform assessment and management decision process (Schindler, 2001).

Future studies should address some of the knowledge gaps identified in this study, such as learning about the impact of multiple stressors that act simultaneously, targeting the species for which we identified a risk of mismatch between larval emergence and their food supply, adding the determination of the future distribution and abundance of key forage species for larvae, juvenile and adult commercial species, so as to be able to include indirect effects in the predictions.

Modelling offers promising ways to unravel the contributions of environmental variables, phenology, food supply and the fishery on the distribution and abundance of exploited species in the future, so as to base management decisions on the best possible scientific knowledge. This includes conservation rules such as marine reserves and closed areas.

4.6 ACKNOWLEDGEMENTS

We would like to thank Alida Bundy, Les Burridge, Michel Comeau, Julien Gaudette, Louise Gendron, Gary Melvin, John Nielson, Mike Power, Bernard Sainte-Marie, Louise Savard, Nancy Shackell, Rob Stephenson and John Tremblay for their comments and expert opinion. This review is part of the contribution of D. Chabot to Working Group 1 of the COST action FA1004 Conservation Physiology of Marine Fishes.

4.7 REFERENCES

Aiken, D.E. and Waddy, S.L. 1986. Environmental influence on recruitment of the American lobster *Homarus americanus*: a perspective. Can. J. Fish. Aquat. Sc., **43**(11): 2258-2270.

Ainsworth, C.H., Samhouri, J.F., Busch, D.S., Cheung, W.W.L., Dunne, J. and Okey, T.A. 2011. Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. ICES J. Mar. Sci., **68**(6): 1217-1229.

Albert, O.T., Nilssen, E.M., Nedreaas, K.H. and Gundersen, A.C. 2001. Distribution and abundance of juvenile Northeast Arctic Greenland halibut (*Reinhardtius hippoglossoides*) in relation to survey coverage and the physical environment. ICES J. Mar. Sci., **58**(5): 1053. doi:10.1006/jmsc.2001.1094.

Allen, J.A. 1959. On the biology of *Pandalus borealis* Kroyer, with reference to a population off the Northumberland coast. J. Mar. Biol. Assoc. UK, **38**(1): 189-220.

Alton, M.S., Bakkala, R.G., Walters, G.E. and Munro, P.T. 1988. Greenland turbot *Reinhardtius hippoglossoides* of the eastern Bering Sea and Aleutian Islands region. NOAA Technical Report NMFS: iii + 31 p.

Alunno-Bruscia, M. and Sainte-Marie, B. 1998. Abdomen allometry, ovary development, and growth of female snow crab, *Chionoecetes opilio* (Brachyura, Majidae), in the northwestern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sc., **55**(2): 459-477.

Annis, E.R., Incze, L.S., Wolff, N. and Steneck, R.S. 2007. Estimates of in situ larval development time for the lobster, *Homarus americanus*. J. Crus. Biol., **27**(3): 454-462.

Anthony, V.C. and Fogarty, M.J. 1985. Environmental effects on recruitment, growth, and vulnerability of Atlantic herring (*Clupea harengus harengus*) in the Gulf of Maine region. Can. J. Fish. Aquat. Sc., **42**(S1): 158-173.

Apollonio, S., Stevenson, D.K. and Dunton Jr, E.E. 1986. Effects of temperature on the biology of the northern shrimp, *Pandalus borealis*, in the Gulf of Maine. NOAA Technical Report NMFS, **42**: iii + 22.

Arnberg, M., Calosi, P., Spicer, J.I., Tandberg, A.H.S., Nilsen, M., Westerlund, S. and Bechmann, R.K. 2012. Elevated temperature elicits greater effects than decreased pH on the development, feeding and metabolism of northern shrimp (*Pandalus borealis*) larvae. Mar. Biol., **160**(8): 2037-2048. doi:10.1007/s00227-012-2072-9.

Astthorsson, O.S., Valdimarsson, H., Gudmundsdottir, A. and Óskarsson, G.J. 2012. Climate-related variations in the occurrence and distribution of mackerel (*Scomber scombrus*) in Icelandic waters. ICES J. Mar. Sci., **69**(7): 1289-1297.

Atkinson, D.B. 1984. Distribution and abundance of beaked redfish in the Gulf of St. Lawrence, 1976--81. J. Northw. Atl. Fish. Sci, **5**: 189-197.

Atkinson, D.B. 1989a. Diel movements of beaked redfish and the implications of these for stratified random bottom trawl estimates of biomass and abundance. N. Am. J. Fish. Manag., **9**(2): 163-170.

Atkinson, D.B. 1989b. Seasonal distribution of sharp-beaked redfish (*Sebastes* spp.) in Northeastern Grand Bank. J. Northw. Atl. Fish. Sci., **9**: 141-150.

Atkinson, D.B., Rose, G.A., Murphy, E.F. and Bishop, C.A. 1997. Distribution changes and abundance of northern cod (*Gadus morhua*), 1981 1993. Can. J. Fish. Aquat. Sc., **54**(S1): 132-138.

Árnason, T., Magnadóttir, B., Björnsson, B., Steinarsson, A. and Björnsson, B.T. 2013. Effects of salinity and temperature on growth, plasma ions, cortisol and immune parameters of juvenile Atlantic cod (*Gadus morhua*). Aquaculture, **380–383**(0): 70-79. doi:10.1016/j.aquaculture.2012.11.036.

Beaugrand, G. and Kirby, R.R. 2010. Climate, plankton and cod. Glob. Change Biol., **16**(4): 1268-1280. doi:10.1111/j.1365-2486.2009.02063.x.

Beaugrand, G., Brander, K.M., Lindley, J., Souissi, S. and Reid, P.C. 2003. Plankton effect on cod recruitment in the North Sea. Nature, **426**(6967): 661-664. doi:10.1038/nature02164.

Bechmann, R.K., Taban, I.C., Westerlund, S., Godal, B.F., Arnberg, M., Vingen, S., Ingvarsdottir, A. and Baussant, T. 2011. Effects of ocean acidification on early life stages of shrimp (*Pandalus borealis*) and mussel (*Mytilus edulis*). J. Toxic. Envir. Health A, **74**(7-9): 424-438. doi:10.1080/15287394.2011.550460.

Benoît, H.P. and MacKinnon, A.-M. 2013. Community and ecosystem-level effects of climate change in Canadian northwest Atlantic waters, pp. 291-312 *In* Climate change impacts, vulnerabilities and opportunities analysis of the marine Atlantic Basin. *Edited by* N.L. Shackell, B.J.W. Greenan, P. Pepin, D. Chabot, A. Warburton. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

Benoît, H.P. and Swain, D.P. 2008. Impacts of environmental change and direct and indirect harvesting effects on the dynamics of a marine fish community. Can. J. Fish. Aquat. Sc., **65**(10): 2088-2104.

Bergström, B.I. 2000. The biology of *Pandalus*. Adv. Mar. Biol., **38**: 55-245.

Bernier, B. and Chabot, D. 2013. Évaluation de l'état du stock de flétan du Groenland (*Reinhardtius hippoglossoides*) du golfe du Saint-Laurent (4RST) en 2010 et description de son régime alimentaire. Secrétariat canadien de consultation scientifique Document de recherche 2012/140: viii + 85 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_140-fra.pdf

Bigelow, H.B. and Schroeder, W.C. 1953. Fishes of the Gulf of Maine. Fish. Bull., **53**(1): 1-577.

Björnsson, B. and Steinarsson, A. 2002. The food-unlimited growth rate of Atlantic cod (*Gadus morhua*). Can. J. Fish. Aquat. Sc., **59**(3): 494-502.

Björnsson, B. and Tryggvadóttir, S.V. 1996. Effects of size on optimal temperature for growth and growth efficiency of immature Atlantic halibut (*Hippoglossus hippoglossus* L.). Aquaculture, **142**(1-2): 33-42.

Björnsson, B., Steinarsson, A. and Oddgeirsson, M. 2001. Optimal temperature for growth and feed conversion of immature cod (*Gadus morhua* L.). ICES J. Mar. Sci., **58**(1): 29-38. doi:10.1006/jmsc.2000.0986.

Björnsson, B., Steinarsson, A. and Árnason, T. 2007. Growth model for Atlantic cod (*Gadus morhua*): effects of temperature and body weight on growth rate. Aquaculture, **271**(1-4): 216-226.

Boudreau, S.A., Anderson, S.C. and Worm, B. 2011. Top-down interactions and temperature control of snow crab abundance in the northwest Atlantic Ocean. Mar. Ecol. Prog. Ser., **429**: 169-183.

Bourdages, H. and Ouellet, J.F. 2011. Geographic distribution and abundance indices of marine fish in the northern Gulf of St. Lawrence (1990-2009). Can. Techn. Rep. Fish. Aquat. Sci. 2963: vi + 171 p. Available from http://www.dfo-mpo.gc.ca/Library/345212.pdf

Bowering, W.R. 1986. The distribution, age and growth and sexual maturity of Atlantic halibut (*Hippoglossus hippoglossus*) in the Newfoundland and Labrador area of the Northwest Atlantic. Can. Techn. Rep. Fish. Aquat. Sci. 1432: iv + 34 p. Available from http://www.dfo-mpo.gc.ca/Library/12966.pdf

Bowering, W.R. and Brodie, W.B. 1991. Distribution of commercial flatfishes in the Newfoundland-Labrador region of the Canadian Northwest Atlantic and changes in certain biological parameters since exploitation. Neth. J. Sea Res., **27**(3): 407-422.

Bowering, B. and Lilly, G.R. 1992. Greenland halibut (*Reinhardtius hippoglossoides*) off Southern Labrador and Northeastern Newfoundland (Northwest Atlantic) feed primarily on capelin (*Mallotus villosus*). Neth. J. Sea Res., **29**(1–3): 211-222. doi:10.1016/0077-7579(92)90021-6.

Bowering, W.R. and Nedreaas, K.H. 2000. A comparison of Greenland halibut (*Reinhardtius hippoglossoides* (Walbaum)) fisheries and distribution in the Northwest and Northeast Atlantic. Sarsia, **85**(1): 61-76.

Brander, K.M. 1994. Patterns of distribution, spawning, and growth in North Atlantic cod: the utility of inter-regional comparisons. ICES Mar. Sci. Symp., **198**.

Brander, K.M. 1995. The effect of temperature on growth of Atlantic cod (*Gadus morhua* L.). ICES J. Mar. Sci., **52**(1): 1.

Brander, K.M. 2010. Cod *Gadus morhua* and climate change: processes, productivity and prediction. J Fish Biol, **77**(8): 1899-1911. doi:10.1111/j.1095-8649.2010.02782.x.

Brêthes, J.-C.F., Coulombe, F., Lafleur, P.-E. and Bouchard, R. 1987. Habitat and spatial distribution of early benthic stages of the snow crab *Chionoecetes opilio* O. Fabricius off the north shore of the Gulf of St. Lawrence. J. Crus. Biol., **7**(4): 667-681.

Brillon, S., Lambert, Y. and Dodson, J. 2005. Egg survival, embryonic development, and larval characteristics of northern shrimp (*Pandalus borealis*) females subject to different temperature and feeding conditions. Mar. Biol., **147**(4): 895-911. doi:10.1007/s00227-005-1633-6.

Brunel, T. and Dickey-Collas, M. 2010. Effects of temperature and population density on von Bertalanffy growth parameters in Atlantic herring: a macro-ecological analysis. Mar. Ecol. Prog. Ser., **405**: 15-28.

Buckley, L.J., Caldarone, E.M. and Lough, R.G. 2004. Optimum temperature and food-limited growth of larval Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) on Georges Bank. Fish. Oceanogr., **13**(2): 134-140. doi:10.1046/j.1365-2419.2003.00278.x.

Bundy, A., Heymans, J.J., Morissette, L. and Savenkoff, C. 2009b. Seals, cod and forage fish: A comparative exploration of variations in the theme of stock collapse and ecosystem change in four Northwest Atlantic ecosystems. Prog. Oceanogr., **81**(1-4): 188-206.

Burmeister, A.D. and Sainte-Marie, B. 2010. Pattern and causes of a temperature-dependent gradient of size at terminal moult in snow crab (*Chionoecetes opilio*) along West Greenland. Polar Biol., **33**(6): 775-788. doi:10.1007/s00300-009-0755-6.

Busby, C.D., Morgan, M.J., Dwyer, K.S., Fowler, G.M., Morin, R., Treble, M., Maddock Parsons, D. and Archambault, D. 2007. Review of the structure, the abundance and distribution of American plaice (*Hippoglossoides platessoides*) in Atlantic Canada in a species-at-risk context. Can. Sc. Adv. Secr. Res. Doc. 2007/069: iv + 90 p. Available from

http://www.dfo-mpo.gc.ca/CSAS/Csas/DocREC/2007/RES2007_069_e.pdf

Campbell, A. 1986. Migratory movements of ovigerous lobsters, *Homarus americanus*, tagged off Grand Manan, Eastern Canada. Can. J. Fish. Aquat. Sc., **43**(11): 2197-2205.

Cargnelli, L.M., Griesbach, S.J. and Morse, W.W. 1999. Atlantic halibut, *Hippoglossus hippoglossus*, life history and habitat characteristics. National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum, **NMFS-NE-125**: v + 17.

Carscadden, J.E., Frank, K.T. and Miller, D.S. 1989. Capelin (*Mallotus villosus*) spawning on the southeast shoal: influence of physical factors past and present. Can. J. Fish. Aquat. Sc., **46**(10): 1743-1754.

Carscadden, J.E., Frank, K.T. and Leggett, W.C. 2001. Ecosystem changes and the effects on capelin (*Mallotus villosus*), a major forage species. Can. J. Fish. Aquat. Sc., **58**(1): 73-85.

Castonguay, M., Rose, G.A. and Leggett, W.C. 1992. Onshore movements of Atlantic mackerel (*Scomber scombrus*) in the northern Gulf of St. Lawrence: associations with wind-forced advections of warmed surface waters. Can. J. Fish. Aquat. Sc., **49**(11): 2232-2241.

Chabot, D. 2004. Chronic non-lethal levels of hypoxia limit distribution and growth of Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence, Canada *In* Proceedings of the 7th International Symposium on Fish Physiology, Toxicology and Water Quality, Tallinn, Estonia, May 12-15, 2003, EPA 600/R-04/049. *Edited by* G.L. Rupp and M.D. White. U.S. Environmental Protection Agency, Ecosystems Research Division, Athens, Georgia, USA. pp. 183-205. Available from http://water.montana.edu/symposium/proceedings/default.htm

Chabot, D. and Claireaux, G. 2008. Environmental hypoxia as a metabolic constraint on fish: the case of Atlantic cod, *Gadus morhua*. Mar. Pollut. Bull., **57**(6-12): 287-294.

Chabot, D. and Dutil, J.-D. 1999. Reduced growth of Atlantic cod in non-lethal hypoxic conditions. J. Fish Biol., **55**(3): 472-491.

Chabot, D. and Gilbert, D. 2008. The impact of hypoxia on cod from the Baltic and the Gulf of St. Lawrence. ICES CM 2008/J:15: 14 p.

Chabot, D. and Gilbert, D. 2013. Description of the Atlantic Large Aquatic Basin as a habitat for marine fish and invertebrates, pp. 1-15 *In* Climate change impacts, vulnerabilities and opportunities analysis of the marine Atlantic Basin. *Edited by* N.L. Shackell, B.J.W. Greenan, P. Pepin, D. Chabot, A. Warburton. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

Chabot, D. and Guénette, S. 2013. Physiology of water breathers: Effects of temperature, dissolved oxygen, salinity and pH, p. 16–44 *In* Climate change impacts, vulnerabilities and opportunities analysis of the marine Atlantic Basin. *Edited by* N.L. Shackell, B.J.W. Greenan, P. Pepin, D. Chabot, A. Warburton. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

Chabot, D. and Ouellet, P. 2005. Rearing *Pandalus borealis* larvae in the laboratory: II – oxygen consumption and ETSA activity at three temperatures. Mar. Biol., **147**: 881-894.

Chabot, D., Rondeau, A., Sainte-Marie, B., Savard, L., Surette, T. and Archambault, P. 2007. Distribution of benthic invertebrates in the Estuary and Gulf of St. Lawrence. Can. Sc. Adv. Secr. Res. Doc., 2007/018: vii + 108 p. Available from http://www.dfo-mpo.gc.ca/CSAS/Csas/DocREC/2007/RES2007_018_a.pdf

Chabot, D., Sainte-Marie, B., Briand, K. and Hanson, J.M. 2008. Atlantic cod and snow crab predator-prey size relationship in the Gulf of St. Lawrence, Canada. Mar. Ecol. Prog. Ser., **363**: 227-240. doi:10.3354/meps07384.

Charmantier, G. and Charmantier-Daures, M. 1995. Osmoregulation and salinity tolerance in zoeae and juveniles of the snow crab *Chionoecetes opilio*. Aquat. Living Resour., **8**(2): 171-179. doi:10.1051/alr:1995014.

Checkley Jr, D.M. 1982. Selective feeding by Atlantic herring (*Clupea harengus*) larvae on zooplankton in natural assemblages. Mar. Ecol. Prog. Ser., **9**: 245-253.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R. and Pauly, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish Fish., **10**(3): 235-251. doi:10.1111/j.1467-2979.2008.00315.x.

Cheung, W.W.L., Dunne, J., Sarmiento, J.L. and Pauly, D. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES J. Mar. Sci., **68**(6): 1008-1018.

Claireaux, G., Webber, D., Kerr, S. and Boutilier, R. 1995. Physiology and behaviour of free-swimming Atlantic cod (*Gadus morhua*) facing fluctuating salinity and oxygenation conditions. J. Exp. Biol., **198**(1): 61.

Claireaux, G., Webber, D.M., Lagardère, J.P. and Kerr, S.R. 2000. Influence of water temperature and oxygenation on the aerobic metabolic scope of Atlantic cod (*Gadus morhua*). J. Sea Res., **44**(3-4): 257-265.

Clark, S.H., Cadrin, S.X., Schick, D.F., Diodati, P.J., Armstrong, M.P. and McCarron, D. 2000. The Gulf of Maine northern shrimp (*Pandalus borealis*) Fishery: a review of the record. J. Northw. Atl. Fish. Sci., **27**: 193-226.

Colette, B.B. 2002. Mackerels, Family Scombridae *In* Bigelow and Schroeder's fishes of the Gulf of Maine. *Edited by* B.B. Colette and G. Klein-MacPhee. Smitsonian Institution Press, Washington. pp. 516-536.

Collins, R., Stansbury, D., Veitch, P. and Janes, J. 2009. Recent trends and management changes in the American lobster (*Homarus americanus*) fishery in Newfoundland. Can. Sc. Adv. Secr. Res. Doc. 2009/096: iv + 29 p. Available from http://www.dfo-mpo.gc.ca/CSAS/Csas/publications/resdocs-docrech/2009/2009_096_e.pdf

Comeau, M., Hanson, J.M., Rondeau, A., Mallet, M. and Chassé, J. 2008. Framework and assessment for American lobster, *Homarus americanus*, fisheries in the southern Gulf of St. Lawrence: LFA 23, 24, 25,26A and 26B. Can. Sc. Adv. Secr. Res. Doc. 2008/054: ii + 111 p. Available from http://www.dfo-mpo.gc.ca/CSAS/Csas/Publications/ResDocs-DocRech/2008/2008_054_e.pdf

Conan, G.Y., Starr, M., Comeau, M., Therriault, J.C., Hernàndez, F.X.M. and Robichaud, G. 1996. Life history strategies, recruitment fluctuations, and management of the Bonne Bay Fjord Atlantic snow crab (*Chionoecetes opilio*). *In:* High Latitude Crabs: Biology, Management, and Economic. pp. 59-97. Lowell Wakefield Fish. Symp. Ser. 96-02. Alaska Sea Grant Coll. Prog. Rep. , Anchorage, AK

Cowan, D.F., Watson, W.H., Solow, A.R. and Mountcastle, A.M. 2007. Thermal histories of brooding lobsters, *Homarus americanus*, in the Gulf of Maine. Mar. Biol., **150**(3): 463-470.

Crossin, G.T., Al-Ayoub, S.A., Jury, S.H., Howell, W.H. and Watson III, W.H. 1998. Behavioral thermoregulation in the American lobster *Homarus americanus*. J. Exp. Biol., **201**(3): 365-374.

D'Amours, D. 1993. The distribution of cod (*Gadus morhua*) in relation to temperature and oxygen level in the Gulf of St. Lawrence. Fish. Oceanogr., **2**: 24-29.

D'Amours, D. and Castonguay, M. 1992. Spring migration of Atlantic mackerel, *Scomber scombrus*, in relation to water temperature through Cabot Strait (Gulf of St. Lawrence). Environ. Biol. Fish., **34**(4): 393-399.

Daoud, D., Chabot, D., Audet, C. and Lambert, Y. 2007. Temperature induced variation in oxygen consumption of juvenile and adult stages of the northern shrimp, *Pandalus borealis*. J. Exp. Mar. Biol. Ecol., **347**(1-2): 30-40.

Daoud, D., Lambert, Y., Audet, C. and Chabot, D. 2010. Size and temperature-dependent variations in intermolt duration and size increment at molt of northern shrimp, *Pandalus borealis*. Mar. Biol., **157**(12): 2655-2666. doi:10.1007/s00227-010-1526-1.

Darbyson, E., Swain, D.P., Chabot, D. and Castonguay, M. 2003. Diel variation in feeding rate and prey composition of herring and mackerel in the southern Gulf of St Lawrence. J. Fish Biol., **63**: 1235-1257.

Davidson, K.G. and Chin, E.A. 1991. A comparison of the taxonomic characteristics and duration of the laboratory reared larvae of snow crabs, *Chionoecetes opilio* (O. Fabricius) and toad crabs,(*Hyas* sp.) from Atlantic Canada. Can. Techn. Rep. Fish. Aquat. Sci. 1762: v + 21 p. Available from http://www.dfo-mpo.gc.ca/Library/116937.pdf

Dawe, E.G., Bowering, W.R. and Joy, J.B. 1998. Predominance of squid (*Gonatus* spp.) in the diet of Greenland halibut (*Reinhardtius hippoglossoides*) on the deep slope of the northeast Newfoundland continental shelf. Fish. Res, **36**: 267-273.

Dawe, E., Koen-Alonso, M., Chabot, D., Stansbury, D. and Mullowney, D. 2012. Trophic interactions between key predatory fishes and crustaceans: comparison of two Northwest Atlantic systems during a period of ecosystem change. Mar. Ecol. Prog. Ser., **469**: 233-248. doi:10.3354/meps10136.

Dawe, E.G., Mullowney, D.R., Moriyasu, M. and Wade, E. 2012. Effects of temperature on size-at-terminal molt and molting frequency in snow crab *Chionoecetes opilio* from two Canadian Atlantic ecosystems. Mar. Ecol. Prog. Ser., **469**: 279-296. doi:10.3354/meps09793.

Despatie, S.-P., Castonguay, M., Chabot, D. and Audet, C. 2001. Final thermal preferendum of Atlantic cod: effect of food ration. Trans. Am. Fish. Soc., **130**: 263-275.

DFO 2009. Assessment of the lobster populations of the North Shore (LFAs 15, 16 and 18) and Anticosti Island (LFA 17) in 2008. Can. Sc. Adv. Secr. Sci. Adv. Rep. 2009/047: 11 p. Available from http://www.dfo-mpo.gc.ca/CSAS/Csas/Publications/SAR-AS/2009/2009_047_e.pdf

DFO 2012a. Assessment of the Atlantic mackerel stock for the northwest Atlantic (Subareas 3 and 4) in 2011. Can. Sc. Adv. Secr. Sci. Adv. Rep. 2012/031: 17 p. Available from http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2012/2012_031-eng.pdf

DFO 2012b. Assessment of the status of 4X5Y haddock in 2011. Can. Sc. Adv. Secr. Sci. Adv. Rep. 2012_023: 14 p. Available from http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2012/2012_023-eng.pdf

Dickey-Collas, M., Engelhard, G.H. and Möllmann, C. 2010. Herring *In* Resolving climate impacts on fish stocks. *Edited by* A.D. Rijnsdorp, M.A. Peck, G.H. Engelhard, C. Möllmann and J.K. Pinnegar. ICES Cooperative Research Report ICES, Copenhagen, Denmark. pp. 121-129.

Dionne, M., Sainte-Marie, B., Bourget, E. and Gilbert, D. 2003. Distribution and habitat selection of early benthic stages of snow crab *Chionoecetes opilio*. Mar. Ecol. Prog. Ser., **259**: 117-128.

Domenici, P., Steffensen, J.F. and Batty, R.S. 2000. The effect of progressive hypoxia on swimming activity and schooling in Atlantic herring. J. Fish Biol., **57**(6): 1526-1538.

Domenici, P., Ferrari, R.S., Steffensen, J.F. and Batty, R.S. 2002. The effect of progressive hypoxia on school structure and dynamics in Atlantic herring *Clupea harengus*. Proc. R. Soc. Lond., Ser. B Biol. Sci., **269**(1505,): 2103-2111.

Dove, A.D., Allam, B., Powers, J.J. and Sokolowski, M.S. 2005. A prolonged thermal stress experiment on the American lobster, *Homarus americanus*. J. Shellfish Res., **24**(3): 761-765.

Drinkwater, K.F. 2002. A review of the role of climate variability in the decline of northern cod. *In:* Fisheries in a Changing Climate. American Fisheries Society Symposium 32 McGinn NA, ed. pp. 113-130, Bethesda, MD, USA

Drinkwater, K.F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES J. Mar. Sci., **62**(7): 1327-1337.

Dupont-Prinet, A., Vagner, M., Chabot, D. and Audet, C. 2013a. Impact of hypoxia on the metabolism of Greenland halibut (*Reinhardtius hippoglossoides*). Can. J. Fish. Aquat. Sc., **70**: 461-469.

Dupont-Prinet, A., Pillet, M., Chabot, D., Hansen, T., Tremblay, R. and Audet, C. 2013b. Northern shrimp (*Pandalus borealis*) oxygen consumption and metabolic enzyme activities are severely constrained by hypoxia in the Estuary and Gulf of St. Lawrence. J. Exp. Mar. Biol. Ecol., **448**: 298-307.

Dutil, J.D. and Brander, K. 2003. Comparing productivity of North Atlantic cod (*Gadus morhua*) stocks and limits to growth production. Fish. Oceanogr., **12**(4-5): 502-512.

Dutil, J.-D., Lambert, Y., Larocque, R. and Sévigny, J.-M. 2003. Temperature preference and tolerance in larval and adult redfish *S. fasciatus* and *S. mentella*, pp. 73-78 *In* Redfish multidisciplinary research zonal program (1995-1998): Final report. *Edited by* D. Gascon. Can. Techn. Rep. Fish. Aquat. Sci. 2462: xiii + 139 p. Available from http://www.dfo-mpo.gc.ca/Library/274564.pdf

Dutil, J.-, Sylvestre, E.-, Gamache, L., Larocque, R. and Guderley, H. 2007. Burst-coast use, swimming performance, and metabolism of Atlantic cod (*Gadus morhua*) in sub-lethal hypoxic conditions. J. Fish Biol., **71**: 1-13.

Dutil, J.-D., Jabouin, C., Larocque, R., Desrosiers, G. and Blier, P.U. 2008. Atlantic cod (*Gadus morhua*) from cold and warm environments differ in their maximum growth capacity at low temperatures. Can. J. Fish. Aquat. Sc., **65**(12): 2579-2591. doi:10.1139/F08-159.

Dwyer, K.S., Buren, A. and Koen-Alonso, M. 2010. Greenland halibut diet in the Northwest Atlantic from 1978-2003 as an indicator of ecosystem change. J. Sea Res., **64**(4): 436-445.

Engelhard, G.H., Pinnegar, J.K., Kell, L.T. and Rijnsdorp, A.D. 2011. Nine decades of North Sea sole and plaice distribution. ICES J. Mar. Sci., **68**(6): 1090-1104.

Ernst, P. 1987. Distribution of Greenland halibut (*Reinhardtius hippoglossoides* Walb.) of the Canadian-West Greenland stock in dependence on the temperature level . NAFO SCR Doc, **87/77**(N1377): 1-13.

Fletcher, G.L., King, M.J. and Kao, M.H. 1987. Low temperature regulation of antifreeze glycopeptide levels in Atlantic cod (*Gadus morhua*). Can. J. Zool., **65**(2): 227-233.

Fonseca, D.B., Sainte-Marie, B. and Hazel, F. 2008. Longevity and change in shell condition of adult male snow crab *Chionoecetes opilio* inferred from dactyl wear and mark-recapture data. Trans. Am. Fish. Soc., **137**(4): 1029-1043. doi:10.1577/T07-079.1.

Foss, A., Kristensen, T., Åtland, Hustveit, H., Hovland, H., Øfsti, A. and Imsland, A.K. 2006. Effects of water reuse and stocking density on water quality, blood physiology and growth rate of juvenile cod (*Gadus morhua*). Aquaculture, **256**(1): 255-263.

Foyle, T.P., O'Dor, R.K. and Elner, R.W. 1989. Energetically defining the thermal limits of the snow crab. J. Exp. Biol., **145**(1): 371-393.

Frank, K.T., Carscadden, J.E. and Simon, J.E. 1996. Recent excursions of capelin (*Mallotus villosus*) to the Scotian Shelf and Flemish Cap during anomalous hydrographic conditions. Can. J. Fish. Aquat. Sc., **53**(7): 1473-1486.

Frommel, A.Y., Schubert, A., Piatkowski, U. and Clemmesen, C. 2013. Egg and early larval stages of Baltic cod, *Gadus morhua*, are robust to high levels of ocean acidification. Mar. Biol., **160**: 1825-1834. doi:10.1007/s00227-011-1876-3.

Fry, F.E.J. 1971. The effect of environmental factors on the physiology of fish *In* Fish physiology, vol. 6. *Edited by* W.S. Hoar and D.J. Randall. Academic Press, New York. pp. 1-98.

Fudge, S.B. and Rose, G.A. 2008. Life history co-variation in a fishery depleted Atlantic cod stock. Fish. Res., **92**(1): 107-113.

Fulton, E.A. 2011. Interesting times: winners, losers, and system shifts under climate change around Australia. ICES J. Mar. Sci., **68**(6): 1329-1342.

Galbraith, P.S., Chassé, J., Larouche, P., Gilbert, D., Brickman, D., Pettigrew, B., Devine, L. and Lafleur, C. 2013. Physical oceanographic conditions in the Gulf of St. Lawrence in 2012. Can. Sc. Adv. Secr. Res. Doc. 2013/026: iii + 89 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2013/2013_026-eng.pdf

Garcia, E.G. 2007. The northern shrimp (*Pandalus borealis*) offshore fishery in the Northeast Atlantic. Adv. Mar. Biol., **52**: 147-266.

Gascon, D. (Editor). 2003. Redfish multidisciplinary research zonal program (1995-1998): Final report. Canadian Technical Report of Fisheries and Aquatic Sciences, 2462. xiii + 139 p. Available from http://www.dfo-mpo.gc.ca/Library/274564.pdf

Gendron, L. and Savard, G. 2012. Lobster stock status in the coastal waters of Québec (LFAs 15 to 22) in 2011 and determination of reference points for the implementation of a precautionary approach in the Magdalen Islands (LFA 22). Can. Sc. Adv. Secr. Res. Doc. 2012/010: xvii + 143 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_010-eng.pdf

Gilbert, D., Sundby, B., Gobeil, C., Mucci, A. and Tremblay, G.- 2005. A seventy-two year record of diminishing deep-water oxygen in the St. Lawrence estuary: the northwest Atlantic connection. Limnol. Oceanogr., **50**(5): 1654-1666.

Gilbert, D., Chabot, D., Archambault, P., Rondeau, B. and Hébert, S. 2007. Appauvrissement en oxygène dans les eaux profondes du Saint-Laurent marin — Causes possibles et impacts écologiques. Nat. Can., **131**(1): 67-75.

Glenn, R.P. and Pugh, T.L. 2006. Epizootic shell disease in American lobster (*Homarus americanus*) in Massachusetts coastal waters: interactions of temperature, maturity, and intermolt duration. J. Crus. Biol., **26**(4): 639-645.

Goddard, S.V., Wroblewski, J.S., Taggart, C.T., Howse, K.A., Bailey, W.L., Kao, M.H. and Fletcher, G.L. 1994. Overwintering of adult northern Atlantic cod (*Gadus morhua*) in cold inshore waters as evidenced by plasma antifreeze glycoprotein levels. Can. J. Fish. Aquat. Sc., **51**(12): 2834-2842.

Gollock, M.J., Currie, S., Petersen, L.H. and Gamperl, A.K. 2006. Cardiovascular and haematological responses of Atlantic cod (*Gadus morhua*) to acute temperature increase. J. Exp. Biol., **209**(15): 2961.

Grégoire, F., Savenkoff, C. and Chabot, D. 2005. Capelin (*Mallotus villosus*) of the Estuary and Gulf of St. Lawrence (NAFO Divisions 4RST) in 2004. Can. Sc. Adv. Secr. Res. Doc. 2005/058: iv + 55 p.

Grégoire, F., Bourdages, H. and Ouellet, J.F. 2011. Analyses of the capelin (*Mallotus villosus*) abundances from the multidisciplinary groundfish and shrimp surveys conducted in the Estuary and northern Gulf of St. Lawrence from 1990 to 2009. Can. Sc. Adv. Secr. Res. Doc. 2011/022: vi + 94 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2011/2011_022-bil.pdf

Grégoire, F., Beaulieu, J.-L., Gendron, M.-H. and LeBlanc, D. 2013. Results of the Atlantic mackerel (*Scomber scombrus* L.) egg survey conducted on the Scotian Shelf and Newfoundland' s South Coast in. Can. Sc. Adv. Secr. Res. Doc. 2012/127: iii + 25 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2012/2012_127-eng.pdf

Guénette, S. and Stephenson, R. 2012. Accounting for predators in ecosystem-based management of herring fisheries of the western Scotian Shelf, Canada *In* Global Progress in Ecosystem-Based Fisheries Management. *Edited by* G.H. Kruse, H.I. Browman, K.L. Cochrane, D. Evans, G.S. Jamieson, P.A. Livingston, D. Woodby and C.I. Zhang. Alaska Sea Grant, University of Alaska, Fairbanks, Alaska. pp. 105-128.

Hardy, D., Munro, J. and Dutil, J.-D. 1994. Temperature and salinity tolerance of the soft-shell and hard-shell male snow crab, *Chionoecetes opilio*. Aquaculture, **122**(2): 249-265.

Harley, C.D. 2011. Climate change, keystone predation, and biodiversity loss. Science, **334**(6059): 1124-1127.

Harley, C.D., Randall Hughes, A., Hultgren, K.M., Miner, B.G., Sorte, C.J., Thornber, C.S., Rodriguez, L.F., Tomanek, L. and Williams, S.L. 2006. The impacts of climate change in coastal marine systems. Ecol. Lett., **9**(2): 228-241.

Hawkins, S.J., Moore, P.J., Burrows, M.T., Poloczanska, E., Mieszkowska, N., Herbert, R.J., Jenkins, S.R., Thompson, R.C., Genner, M.J. and Southward, A.J. 2008. Complex interactions in a rapidly changing world: responses of rocky shore communities to recent climate change. Clim. Res., **37**(CR Special 18): 123-133.

Haynes, E.B. 1983. Distribution and abundance of larvae of king crab, *Paralithodes camtschatica*, and pandalid shrimp in the Kachemak Bay Area, Alaska, 1972 and 1976. NOAA Technical Report NMFS SSRF-765: iii + 64 p.

Herbert, N.A. and Steffensen, J.F. 2006. Hypoxia increases the behavioural activity of schooling herring: a response to physiological stress or respiratory distress? Mar. Biol., **149**(5): 1217-1225.

Hew, C.L., Slaughter, D., Fletcher, G.L. and Joshi, S.B. 1981. Antifreeze glycoproteins in the plasma of Newfoundland Atlantic cod (*Gadus morhua*). Can. J. Zool., **59**(11): 2186-2192.

Hobday, A.J. 2010. Ensemble analysis of the future distribution of large pelagic fishes off Australia. Prog. Oceanogr., **86**(1): 291-301.

Houlihan, D.F., Govind, C.K. and El-Haj, A. 1985. Energetics of swimming in *Callinectes sapidus* and walking in *Homarus americanus*. Comp. Biochem. Physiol. A, **82A**: 267-279.

Howell, W.H. and Caldwell, M.A. 1984. Influence of temperature on energy utilization and growth of embryonic and prolarval American plaice, *Hippoglossoides platessoides* (Fabricius). J. Exp. Mar. Biol. Ecol., **79**(2): 173-189.

Howell, P., Benway, J., Giannini, C., McKown, K., Burgess, R. and Hayden, J. 2005. Long-term population trends in American lobster (*Homarus americanus*) and their relation to temperature in Long Island Sound. J. Shellfish Res., **24**(3): 849-857.

Hudon, C. 1994. Large-scale analysis of Atlantic Nova Scotia American lobster (*Homarus americanus*) landings with respect to habitat, temperature, and wind conditions. Can. J. Fish. Aquat. Sc., **51**(6): 1308-1321.

Huse, G. and Ellingsen, I. 2008. Capelin migrations and climate change—a modelling analysis. Climatic Change, **87**(1): 177-197.

Hutchings, J.A. 2005. Life history consequences of overexploitation to population recovery in Northwest Atlantic cod (*Gadus morhua*). Can. J. Fish. Aquat. Sc., **62**(4): 824-832.

Hutchings, J.A. and Myers, R.A. 1993. Effect of age on the seasonality of maturation and spawning of Atlantic cod, *Gadus morhua*, in the Northwest Atlantic. Can. J. Fish. Aquat. Sc., **50**(11): 2468-2474.

ICES 2011. Report of the Arctic Fisheries Working Group (AFWG). ICES CM 2011/ACOM:05: 659 p.

Jansen, T. and Gislason, H. 2011. Temperature affects the timing of spawning and migration of North Sea mackerel. Cont. Shelf Res., **31**(1): 64-72. doi:10.1016/j.csr.2010.11.003.

Jobling, M. 1988. A review of the physiological and nutritional energetics of cod, *Gadus morhua* L., with particular reference to growth under farmed conditions. Aquaculture, **70**(1-2): 1-19.

Johnson, D.L., Berrien, P.L., Morse, W.W. and Vitaliano, J.J. 1999. Essential fish habitat source document: American plaice, *Hippoglossoides platessoides*, life history and habitat characteristics. NOAA Technical Memorendum NMFS-NE-123: v + 31 p.

Jordan, A.D. and Steffensen, J.F. 2007. Effects of ration size and hypoxia upon specific dynamic action (SDA) in the cod. Physiol. Biochem. Zool., **80**(2): 178-185.

Jørgensen, O.A. 1997. Movement patterns of Greenland halibut, *Reinhardtius hippoglossoides* (Walbaum), at west Greenland, as inferred from trawl survey distribution and size data. J. Northw. Atl. Fish. Sci., **21**: 23-38.

Kelly, G.F. and Barker, A.M. 1961. Vertical distribution of young redfish in the Gulf of Maine. ICNAF Special Publication, **3**: 220-233.

Keppel, E.A., Scrosati, R.A. and Courtenay, S.C. 2012. Ocean acidification decreases growth and development in American lobster (*Homarus americanus*) larvae. J. Northw. Atl. Fish. Sci., **44**: 61-66.

Klein-MacPhee, G. and Colette, B.B. 2002. Scorpionfishes. Family Scorpaenidae *In* Bigelow and Schroeder's fishes of the Gulf of Maine. *Edited by* B.B. Colette and G. Klein-MacPhee. Smitsonian Institution Press, Washington. pp. 331-338.

Koeller, P.A. 2000. Relative importance of Abiotic and Biotic factors to the management of the northern shrimp (*Pandalus borealis*) fishery on the Scotian shelf. J. Northw. Atl. Fish. Sci., **27**: 21-33.

Koeller, P., Fuentes-Yaco, C., Platt, T., Sathyendranath, S., Richards, A., Ouellet, P., Orr, D., Skuladottir, U., Wieland, K., Savard, L. and Aschan, M. 2009. Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Science, **324**(5928): 791-793. doi:10.1126/science.1170987.

Kogane, T., Hamasaki, K. and Nogami, K. 2005. Effect of temperature on survival and developmental period of larval snow crab *Chionoecetes opilio* (Brachyura: Majidae) reared in the laboratory. Nippon Suisan Gakk., **71**(2): 161-164.

Kon, T. 1980. Studies on the life history of the zuwai crab, *Chionoecetes opilio* (O. Fabricius). Special Publication Sado Marine Biolological Station Niigata Univiversity 2: 64 p.

Kon, T., Adachi, T. and Suzuki, Y. 2003. Distribution of snow crab, *Chionoecetes* spp., larvae off Wakasa Bay in the Sea of Japan. Fish. Sc., **69**(6): 1109-1115.

Kroeker, K.J., Kordas, R.L., Crim, R.N. and Singh, G.G. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol. Lett., **13**(11): 1419-1434.

Kuhn, P.S., Graham, S. and Choi, J.S. 2011. Influence of senescent algae, temperature, tides, currents, and embryo detachment on *Chionoecetes opilio* (Snow crab) larval release. J. Crus. Biol., **31**(1): 100-105.

Kulka, D.W., Wroblewski, J.S. and Narayanan, S. 1995. Recent changes in the winter distribution and movements of northern Atlantic cod (*Gadus morhua* Linnaeus, 1758) on the Newfoundland-Labrador Shelf. ICES J. Mar. Sci., **52**(6): 889-902.

Lafrance, P., Castonguay, M., Chabot, D. and Audet, C. 2005. Ontogenetic changes in temperature preference of Atlantic cod. J. Fish Biol., **66**: 553-567.

Lambert, Y. 2011. Environmental and fishing limitations to the rebuilding of the northern Gulf of St. Lawrence cod stock (*Gadus morhua*). Can. J. Fish. Aquat. Sc., **68**(4): 618-631.

Lambert, Y., Dutil, J.D. and Munro, J. 1994. Effects of intermediate and low salinity conditions on growth rate and food conversion of Atlantic cod (*Gadus morhua*). Can. J. Fish. Aquat. Sc., **51**: 1569-1576.

Lannig, G., Bock, C., Sartoris, F.J. and Pörtner, H.O. 2004. Oxygen limitation of thermal tolerance in cod, *Gadus morhua* L., studied by magnetic resonance imaging and on-line venous oxygen monitoring. Am J Physiol Regul Integr Comp Physiol, **287**(4): R902-R910. doi:10.1152/ajpregu.00700.2003.

Lanteigne, M. 1985. Distribution spatio-temporelle des larves de crabe appartenant aux genres *Chionoecetes* et *Hyas*, dans la Baie des Chaleurs, Canada. M.Sc. thesis. Université de Moncton, Nouveau-Brunswick. xi + 161 pp.

Laurence, G.C. and Rogers, C.A. 1976. Effects of temperature and salinity on comparative embryo development and mortality of Atlantic cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* (L.)). ICES J. Mar. Sci., **36**(3): 220-228. doi:10.1093/icesjms/36.3.220.

Laurence, G.C. 1978. Comparative growth, respiration and delayed feeding abilities of larval cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) as influenced by temperature during laboratory studies. Mar. Biol., **50**(1): 1-7. doi:10.1007/BF00390536.

Lawson, J.W. and Stenson, G.B. 1997. Diet of northwest Atlantic harp seals (*Phoca groenlandica*) in offshore areas. Can. J. Zool., **75**(12): 2095-2106.

Leggett, W.C., Frank, K.T. and Carscadden, J.E. 1984. Meteorological and hydrographic regulation of year-class strength in capelin (*Mallotus villosus*). Can. J. Fish. Aquat. Sc., **41**(8): 1193-1201.

Lehodey, P., Alheit, J., Barange, M., Baumgartner, T., Beaugrand, G., Drinkwater, K., Fromentin, J.M., Hare, S.R., Ottersen, G., Perry, R.I., Roy, C., van der Lingen, C.D. and Werner, F. 2006. Climate variability, fish, and fisheries. J. Climate, **19**(20): 5009-5030.

Lilly, G.R. 1991. Interannual variability in predation by cod (*Gadus morhua*) on capelin (*Mallotus villosus*) and other prey off southern Labrador and northeastern Newfoundland. ICES Mar. Sci. Symp., **193**: 133-146.

Lilly, G.R. 2008. The decline, recovery, and collapse of Atlantic cod (*Gadus morhua*) off Labrador and eastern Newfoundland. *In:* Resiliency of gadid stocks to fishing and climate change. Lowell Wakefield Fisheries Symposium 31 Oct.–3 Nov. 2006. Kruse GH, Drinkwater K, Iamelli JN, Link JS, Stram DL, Wespestad V, Woodby D, eds. pp. 67-88 AK-SG-08-01. AK-SG-08-01. Alaska Sea Grant College Program, Anchorage

Lilly, G.R., Shelton, P.A., Brattey, J., Cadigan, N.G., Murphy, E.F. and Stansbury, D.E. 1999. An assessment of the cod stock in NAFO Divisions 2J+3KL. Can. Stock Asses. Secr. Res. Doc. 99/42: 165 p.

Lilly, G.R., Parsons, D.G. and Kulka, D.W. 2000. Was the increase in shrimp biomass on the Northeast Newfoundland Shelf a consequence of a release in predation pressure from cod? J. Northw. Atl. Fish. Sci., **27**: 45-62.

Lilly, G.R., Wieland, K., Rothschild, B.J., Sundby, S., Drinkwater, K.F., Brander, K., Ottersen, G., Carscadden, J.E., Stenson, G.B., Chouinard, G.A., Swain, D.P., Daan, N., Enberg, K., Hammill, M.O., Rosing-Asvid, A., Svedäng, H. and Vásquez, A. 2008. Decline and recovery of Atlantic cod (*Gadus morhua*) stocks throughout the North Atlantic *In* Resiliency of gadid stocks to fishing and climate change. *Edited by* Alaska Sea Grant College Program Vol. AK-SG-08-01. pp. 39-66.

Lim, Y.-S., Lee, J.-K., Lee, J.-H., Lee, B.-K. and Hur, S.-B. 2001. Morphology of snow crab, *Chionoecetes opilio* larvae and larval growth at different water temperatures. Journal of Aquaculture, **14**(1): 51-56.

Loder, J.W., Chassé, J., Galbraith, P., Han, D., Lavoie, D., and others. 2013. Summary of climate change trends and projections for the Atlantic Large Aquatic Basin off Canada. Can. Techn. Rep. Fish. Aquat. Sci. 3051: (under revision) p.

Longhurst, A. 2002. Murphy's law revisited: longevity as a factor in recruitment to fish populations. Fish. Res., **56**(2): 125-131.

Lovrich, G.A. and Sainte-Marie, B. 1997. Cannibalism in the snow crab, *Chionoecetes opilio* (O. Fabricius) (Brachyura: Majidae), and its potential importance to recruitment. J. Exp. Mar. Biol. Ecol., **211**(2): 225-245.

Lovrich, G.A., Sainte-Marie, B. and Smith, B.D. 1995. Depth distribution and seasonal movements of *Chionoecetes opilio* (Brachyura: Majidae) in Baie Sainte-Marguerite, Gulf of Saint Lawrence. Can. J. Zool., **73**: 1712-1726.

MacKenzie, B.R. 1988. Assessment of temperature effects on interrelationships between stage durations, mortality, and growth in laboratory-reared *Homarus americanus* Milne Edwards larvae. J. Exp. Mar. Biol. Ecol., **116**(1): 87-98.

MacKinnon, J.C. 1973. Metabolism and its relationship with growth rate of American plaice, *Hippoglossoides platessoides* Fabr. J. Exp. Mar. Biol. Ecol., **11**(3): 297-310.

Mantzouni, I. and MacKenzie, B.R. 2010. Productivity responses of a widespread marine piscivore, *Gadus morhua*, to oceanic thermal extremes and trends. Proc Biol Sci, **277**(1689): 1867-1874. doi:10.1098/rspb.2009.1906.

Marcello, A., Mueter, J., Dawe, G. and Moriyasu, M. 2012. Effects of temperature and gadid predation on snow crab recruitment: comparisons between the Bering Sea and Atlantic Canada. Mar. Ecol. Prog. Ser., **469**: 249-261. doi:10.3354/meps09766.

Marshall, C.T., Kjesbu, O.S., Yaragina, N.A., Solemdal, P. and Ulltang, Ø. 1998. Is spawner biomass a sensitive measure of the reproductive and recruitment potential of Northeast Arctic cod? Can. J. Fish. Aquat. Sc., **55**(7): 1766-1783.

Martell, .J., Kieffer, .D. and Trippel, .A. 2005. Effects of temperature during early life history on embryonic and larval development and growth in haddock. J. Fish Biol., **66**(6): 1558-1575. doi:10.1111/j.0022-1112.2005.00699.x.

McLeese, D.W. 1956. Effects of temperature, salinity and oxygen on the survival of the American lobster. J. Fish. Res. Board Can., **13**(2): 247-272.

McLeese, D.W. 1964. Oxygen consumption of the lobster, *Homarus americanus* Milne-Edwards. Helgoland Marine Research, **10**(1): 7-18.

McLeese, D.W. and Watson, J. 1968a. Oxygen consumption of the spider crab (*Chionoecetes opilio*) and the American lobster (*Homarus americanus*) at a low temperature. J. Fish. Res. Board Can., **25**(8): 1729-1732.

McLeese, D.W. and Watson, J. 1968b. Oxygen consumption of the spider crab (*Chionoecetes opilio*) and the American lobster (*Homarus americanus*) at a low temperature. J. Fish. Res. Board Can., **25**(8): 1729-1732.

McQuinn, I.H. 1997. Metapopulations and the Atlantic herring. Rev. Fish Biol. Fish., **7**(3): 297-329.

Melvin, G.D. and Stephenson, R.L. 2007. The dynamics of a recovering fish stock: Georges Bank herring. ICES J. Mar. Sci., **64**(1): 69-82.

Melvin, G.D., Stephenson, R.L. and Power, M.J. 2009a. Oscillating reproductive strategies of herring in the western Atlantic in response to changing environmental conditions. ICES J. Mar. Sci., **66**(8): 1784-1792.

Melzner, F., Göbel, S., Langenbuch, M., Gutowska, M.A., Pörtner, H.O. and Lucassen, M. 2009. Swimming performance in Atlantic cod (*Gadus morhua*) following long-term (4–12 months) acclimation to elevated seawater $P_{CO2.}$ Aquat. Toxicol., **92**(1): 30-37. doi:10.1016/j.aquatox.2008.12.011.

Melzner, F., Thomsen, J., Koeve, W., Oschlies, A., Gutowska, M.A., Bange, H.W., Hansen, H.P. and Körtzinger, A. 2012. Future ocean acidification will be amplified by hypoxia in coastal habitats. Mar. Biol., **160**: 1875-1888. doi:10.1007/s00227-012-1954-1.

Miller, D., Poucher, S. and Coiro, L. 2002. Determination of lethal dissolved oxygen levels for selected marine and estuarine fishes, crustaceans, and a bivalve. Mar. Biol., **140**(2): 287-296. doi:10.1007/s002270100702.

Moran, D. and Stottrup, J.G. 2011. The effect of carbon dioxide on growth of juvenile Atlantic cod *Gadus morhua* L. Aquat Toxicol, **102**(1-2): 24-30. doi:10.1016/j.aquatox.2010.12.014.

Morgan, M.J. and Brodie, W.B. 1991. Seasonal distribution of American plaice on the northern Grand Banks. Mar. Ecol. Prog. Ser., **75**: 101-107.

Morgan, M.J. 1992. Low-Temperature Tolerance of American Plaice in Relation to Declines in Abundance. Trans. Am. Fish. Soc, **121**(3): 399-402. doi:10.1577/1548-8659(1992)121<0399:LTOAPI>2.3.CO;2.

Morgan, M.J. 1993. Ration level and temperature preference of American plaice. Mar. Freshwat. Behav. Physiol., **24**(2): 117-122. doi:10.1080/10236249309378884.

Morgan, M.J. 2000. Interactions between substrate and temperature preference in adult American plaice (*Hippoglossoides platessoides*). Mar. Freshwat. Behav. Physiol., **33**(4): 249-259. doi:10.1080/10236240009387096.

Moriyasu, M. and Lanteigne, C. 1998. Embryo development and reproductive cycle in the snow crab, *Chionoecetes opilio* (Crustacea: Majidae), in the southern Gulf of St. Lawrence, Canada. Can. J. Zool., **76**(11): 2040-2048.

Mowbray, F.K. 2012. Some results from spring acoustic surveys for capelin (*Mallotus villosus*) in NAFO Division 3L between 1982 and 2010. Can. Sc. Adv. Secr. Res. Doc. 2012/143: ii + 34 p.

Möllmann, C., Müller-Karulis, B., Kornilovs, G. and St John, M.A. 2008. Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascade, and feedback loops in a simple ecosystem. ICES J. Mar. Sci., **65**(3): 302-310.

Möllmann, C., Diekmann, R., Müller-Karulis, B., Kornilovs, G., Plikshs, M. and Axe, P. 2009. Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: a discontinuous regime shift in the Central Baltic Sea. Glob. Change Biol., **15**(6): 1377-1393.

Mucci, A., Starr, M., Gilbert, D. and Sundby, B. 2011. Acidification of Lower St. Lawrence Estuary Bottom Waters. Atmosphere-Ocean, **49**(3): 206-218. doi:10.1080/07055900.2011.599265.

Munro, J. and Therriault, J.-C. 1983. Migrations saisonnières du homard (*Homarus americanus*) entre la côte et les lagunes des Îles-de-la-Madeleine. Can. J. Fish. Aquat. Sc., **40**(7): 905-918.

Munro, J., Audet, C., Besner, M. and Dutil, J.-D. 1994. Physiological response of American plaice *(Hippoglossoides platessoides*) exposed to low salinity. Can. J. Fish. Aquat. Sc., **51**(11): 2448-2456.

Myers, R.A., Drinkwater, K.F., Barrowman, N.J. and Baird, J.W. 1993. Salinity and recruitment of Atlantic cod (*Gadus morhua*) in the Newfoundland region. Can. J. Fish. Aquat. Sc., **50**(8): 1599-1609.

Nakashima, B.S., Wheeler, J.P. 2002. Capelin (*Mallotus villosus*) spawning behaviour in Newfoundland waters--the interaction between beach and demersal spawning. ICES J. Mar. Sci., **59**(5): 909-916.

Neilson, J.D., Kearney, J.F., Perley, P. and Sampson, H. 1993. Reproductive biology of Atlantic halibut (*Hippoglossus hippoglossus*) in Canadian waters. Can. J. Fish. Aquat. Sc., **50**(3): 551-563.

Neuenfeldt, S. 2002. The influence of oxygen saturation on the distributional overlap of predator (cod, *Gadus morhua*) and prey (herring, *Clupea harengus*) in the Bornholm Basin of the Baltic Sea. Fish. Oceanogr., **11**(1): 11-17. doi:10.1046/j.1365-2419.2002.00183.x.

Neuenfeldt, S. and Beyer, J.E. 2003. Oxygen and salinity characteristics of predator-prey distributional overlaps shown by predatory Baltic cod during spawning. J. Fish Biol., **62**(1): 168-183. doi:doi:10.1046/j.1095-8649.2003.00013.x.

Neuenfeldt, S., Andersen, K.H. and Hinrichsen, H.H. 2009. Some Atlantic cod *Gadus morhua* in the Baltic Sea visit hypoxic water briefly but often. J. Fish Biol., **75**: 290-294.

Ni, I.H. and Sandeman, E.J. 1984. Size at maturity for Northwest Atlantic redfishes (*Sebastes*). Can. J. Fish. Aquat. Sc., **41**(12): 1753-1762.

Nissling, A. and Westin, L. 1997. Salinity requirements for successful spawning of Baltic and Belt Sea cod and the potential for cod stock interactions in the Baltic Sea. Mar. Ecol. Prog. Ser., **152**: 261-271.

Nissling, A., Kryvi, H. and Vallin, L. 1994. Variation in egg buoyancy of Baltic cod *Gadus morhua* and its implications for egg survival in prevailing conditions in the Baltic Sea. Mar. Ecol. Prog. Ser., **110**(1): 67-74.

Nunes, P. and Nishiyama, T. 1984. Effects of temperature on the embryonic development of the northern pink shrimp *Pandalus borealis* Krøyer. J. Shellfish Res., **4**: 96-97.

O'Brien, C.M., Fox, C.J., Planque, B. and Casey, J. 2000. Climate variability and North Sea cod. Nature, **404**(6774): 142.

Orensanz, J., Ernst, B., Armstrong, D.A., Stabeno, P. and Livingston, P. 2004. Contraction of the geographic range of distribution of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea: an environmental ratchet? California Cooperative Oceanic Fisheries Investigations Reports, **45**: 67-79.

Orlova, E.L., Boitsov, V.D., Dolgov, A.V., Rudneva, G.B. and Nesterova, V.N. 2005. The relationship between plankton, capelin, and cod under different temperature conditions. ICES J. Mar. Sci., **62**(7): 1281-1292.

Orlova, L., Rudneva, B., Renaud, E., Eiane, K., Savinov, V. and Yurko, S. 2010. Climate impacts on feeding and condition of capelin *Mallotus villosus* in the Barents Sea: Evidence and mechanisms from a data set spanning 30 years. Aquat. Biol., **10**: 105-118. doi:10.3354/ab00265.

Orr, D.C. and Bowering, W.R. 1997. A multivariate analysis of food and feeding trends among Greenland halibut (*Reinhardtius hippoglossoides*) sampled in Davis Strait, during 1986. ICES J. Mar. Sci., **54**(5): 819-829.

Otterlei, E., Nyhammer, G., Folkvord, A. and Stefansson, S.O. 1999. Temperature- and size-dependent growth of larval and early juvenile Atlantic cod (*Gadus morhua*): a comparative study of Norwegian coastal cod and northeast Arctic cod. Can. J. Fish. Aquat. Sc., **56**(11): 2099-2111.

Ouellet, P. and Chabot, D. 2005. Rearing *Pandalus borealis* (Krøyer) larvae in the laboratory. Mar. Biol., **147**(4): 869-880. doi:10.1007/s00227-005-1625-6.

Ouellet, P. and Lefaivre, D. 1994. Vertical distribution of northern shrimp (*Pandalus borealis*) larvae in the Gulf of St Lawrence; implications for trophic interactions and transport. Can. J. Fish. Aquat. Sc., **51**(1): 123-132.

Ouellet, P., Savard, L. and Larouche, P. 2007. Spring oceanographic conditions and northern shrimp *Pandalus borealis* recruitment success in the north-western Gulf of St. Lawrence. Mar. Ecol. Prog. Ser., **339**: 229-241.

Overholtz, W.J. and Link, J.S. 2007. Consumption impacts by marine mammals, fish, and seabirds on the Gulf of Maine—Georges Bank Atlantic herring (*Clupea harengus*) complex during the years 1977--2002. ICES J. Mar. Sci., **64**(1): 83-96.

Overholtz, W.J., Armstrong, R.S., Mountain, D.G. and Tercerio, M. 1991. Factors influencing spring distribution, availability, and recreational catch of Atlantic mackerel (*Scomber scombrus*) in the Middle Atlantic and southern New England regions. NOAA Technical Memorandum NMFS-F/NEC-85: iii + 13 p.

Overholtz, W.J., Hare, J.A. and Keith, C.M. 2011. Impacts of interannual environmental forcing and climate change on the distribution of Atlantic mackerel on the US Northeast continental shelf. Mar. Coast. Fish., **3**(1): 219-232.

Page, F.H. and Frank, K.T. 1989. Spawning time and egg stage duration in Northwest Atlantic haddock (*Melanogrammus aeglefinus*) stocks with emphasis on Georges and Browns Bank. Can. J. Fish. Aquat. Sc., **46**(S1): 68-81.

Pane, E.F. and Barry, J.P. 2007. Extracellular acid-base regulation during short-term hypercapnia is effective in a shallow-water crab, but ineffective in a deep-sea crab. Mar. Ecol. Prog. Ser., **334**: 1-9.

Paul, A.J. and Nunes, P. 1983. Temperature modification of respiratory metabolism and caloric intake of *Pandalus borealis* (Krøyer) first zoeae. J. Exp. Mar. Biol. Ecol., **66**(2): 163-168.

Peck, M.A., Buckley, L.J., Caldarone, E.M. and Bengtson, D.A. 2003. Effects of food consumption and temperature on growth rate and biochemical-based indicators of growth in early juvenile Atlantic cod *Gadus morhua* and haddock *Melanogrammus aeglefinus*. Mar. Ecol. Prog. Ser., **251**: 233-243.

Pecl, G.T. and Jackson, G.D. 2008. The potential impacts of climate change on inshore squid: biology, ecology and fisheries. Rev. Fish Biol. Fish., **18**(4): 373-385. doi:10.1007/s11160-007-9077-3.

Peklova, I., Hussey, E., Hedges, J., Treble, A. and Fisk, T. 2012. Depth and temperature preferences of the deepwater flatfish Greenland halibut *Reinhardtius hippoglossoides* in an Arctic marine ecosystem. Mar. Ecol. Prog. Ser., **467**: 193-205. doi:10.3354/meps09899.

Penkoff, P. and Thurberg, T. 1982. Changes in oxygen consumption of the american lobster, *Homarus americanus*, during the molt cycle. Comp. Biochem. Physiol. A, **72**(4): 621-622. doi:10.1016/0300-9629(82)90137-2.

Perry, A.L., Low, P.J., Ellis, J.R. and Reynolds, J.D. 2005. Climate change and distribution shifts in marine fishes. Science, **308**(5730): 1912-1915.

Perry, R.I., Cury, P., Brander, K., Jennings, S., Möllmann, C. and Planque, B. 2010. Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. J. Mar. Syst., **79**(3-4): 427-435.

Peterson, W.T. and Ausubel, S.J. 1984. Diets and selective feeding by larvae of Atlantic mackerel *Scomber scombrus* on zooplankton. Mar. Ecol. Prog. Ser., **17**(1): 65-75.

Petitgas, P., Rijnsdorp, A.D., Dickey-Collas, M., Engelhard, G.H., Peck, M.A., Pinnegar, J.K., Drinkwater, K., Huret, M. and Nash, R.D.M. 2013. Impacts of climate change on the complex life cycles of fish. Fish. Oceanogr., **22**(2): 121-139. doi:10.1111/fog.12010.

Pezzack, D.S. and Duggan, D.R. 1986. Evidence of migration and homing of lobsters (*Homarus americanus*) on the Scotian Shelf. Can. J. Fish. Aquat. Sc., **43**(11): 2206-2211.

Pérez-Casanova, .C., Afonso, L.O.B., Johnson, .C., Currie, S. and Gamperl, .K. 2008. The stress and metabolic responses of juvenile Atlantic cod *Gadus morhua* L. to an acute thermal challenge. J. Fish Biol., **72**(4): 899-916. doi:10.1111/j.1095-8649.2007.01763.x.

Pihl, L. 1994. Changes in the diet of demersal fish due to eutrophication-induced hypoxia in the Kattegat, Sweden. Can. J. Fish. Aquat. Sc., **51**: 321-336.

Pikanowski, R.A., Morse, W.W., Berrien, P.L., Johnson, D.L. and McMillan, D.G. 1999. Essential fish habitat source document: Redfish, *Sebastes* spp., life history and habitat characteristics. NOAA Technical Memorandum NMFS-NE-132: v + 19 p.

Pike, D.G. 1994. The fishery for Greenland halibut (*Reinhardtius hippoglossoides*) in Cumberland Sound, Baffin Island, 1987-1992. Can. Techn. Rep. Fish. Aquat. Sci. 1924: iv + 20 p. Available from http://www.dfo-mpo.gc.ca/Library/178888.pdf

Pitt, T.K. 1966. Sexual maturity and spawning of the American plaice, *Hippoglossoides platessoides* (Fabricius), from Newfoundland and Grand Bank areas. Journal of the Fisheries Board of Canada, **23**(5): 651-672.

Planque, B. and Frédou, T. 1999. Temperature and the recruitment of Atlantic cod (*Gadus morhua*). Can. J. Fish. Aquat. Sc., **56**(11): 2069-2077.

Planque, B., Fromentin, J.M., Cury, P., Drinkwater, K.F., Jennings, S., Perry, R.I. and Kifani, S. 2010. How does fishing alter marine populations and ecosystems sensitivity to climate? J. Mar. Syst., **79**(3-4): 403-417.

Plante, S., Chabot, D. and Dutil, J.D. 1998. Hypoxia tolerance in Atlantic cod. J. Fish Biol., **53**(6): 1342-1356.

Power, M.J., Knox, D. and Melvin, G.D. 2010. 2010 Evaluation of 4VWX herring. Can. Sc. Adv. Secr. Res. Doc. 2010/112: vi + 124 p.

Powles, P.M. 1965. Life history and ecology of American plaice (*Hippoglossoides platessoides* F.) in the Magdalen Shallows. Journal of the Fisheries Board of Canada, **22**(2): 565-598.

Pörtner, H.O. 2001. Climate change and temperature-dependent biogeography: oxygen limitation of thermal tolerance in animals. Naturwissenschaften, **88**(4): 137-146.

Pörtner, H.O. and Farrell, A.P. 2008. Physiology and climate change. Science, **322**: 690-692.

Pörtner, H.O. and Peck, M.A. 2010. Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J. Fish Biol., **77**(8): 1745-1779. doi:10.1111/j.1095-8649.2010.02783.x.

Pörtner, H.O., Berdal, B., Blust, R., Brix, O., Colosimo, A., De Wachter, B., Giuliani, A., Johansen, T., Fischer, T. and Knust, R. 2001. Climate induced temperature effects on growth performance, fecundity and recruitment in marine fish: developing a hypothesis for cause and effect relationships in Atlantic cod (*Gadus morhua*) and common eelpout (*Zoarces viviparus*). Cont. Shelf Res., **21**(18-19): 1975-1997.

Qadri, S.A., Camacho, J., Wang, H., Taylor, J.R., Grosell, M. and Worden, M.K. 2007. Temperature and acid–base balance in the American lobster *Homarus americanus*. J. Exp. Biol., **210**(7): 1245-1254.

Rand, K.M. and Logerwell, E.A. 2011. The first demersal trawl survey of benthic fish and invertebrates in the Beaufort Sea since the late 1970s. Polar Biol., **34**(4): 475-488.

Rasmussen, T. and Aschan, M. 2011. Larval stages of *Pandalus borealis*. Marine Biology Research, **7**(2): 109-121.

Rasmussen, T. and Tande, K. 1995. Temperature-dependent development, growth and mortality in larvae of the deep-water prawn *Pandalus borealis* reared in the laboratory. Mar. Ecol. Prog. Ser., **118**(1): 149-157.

Rätz, H.J. and Lloret, J. 2003. Variation in fish condition between Atlantic cod (*Gadus morhua*) stocks, the effect on their productivity and management implications. Fish. Res., **60**(2): 369-380.

Reid, R.N., Cargnelli, L.M., Griesbach, S.J., Packer, D.B., Johnson, D.L., Zetlin, C.A., Morse, W.W. and Berrien, P.L. 1999. Essential fish habitat source document: Atlantic herring, *Clupea harengus*, life history and habitat characteristics. NOAA Technical Memorandum. NMFS-NE, **126**: v + 48 p.

Ries, J.B., Cohen, A.L. and McCorkle, D.C. 2009. Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. Geology, **37**(12): 1131-1134.

Robichaud, D.A., Bailey, R.F.J. and Elner, R.W. 1989. Growth and distribution of snow crab, *Chionoecetes opilio*, in the southeastern Gulf of St. Lawrence. J. Shellfish Res., **8**: 13-23.

Robichaud, D.A., Elner, R.W. and Bailey, R.F.J. 1991. Differential selection of crab *Chionoecetes opilio* and *Hyas* spp. as prey by sympatric cod *Gadus morhua* and thorny skate *Raja radiata*. Fish. Bull., **89**: 669-680.

Rombouts, I., Beaugrand, G. and Dauvin, J.-C. 2012. Potential changes in benthic macrofaunal distributions from the English Channel simulated under climate change scenarios. Est. Coast. Shelf Sci., **99**: 153-161. doi:10.1016/j.ecss.2011.12.026.

Rose, G. 2005. Capelin (*Mallotus villosus*) distribution and climate: a sea "canary" for marine ecosystem change. ICES J. Mar. Sci., **62**(7): 1524-1530. doi:10.1016/j.icesjms.2005.05.008.

Rose, G.A., Atkinson, B.A., Baird, J., Bishop, C.A. and Kulka, D.W. 1994. Changes in distribution of Atlantic cod and thermal variations in Newfoundland waters, 1980-1992. ICES Mar. Sci. Symp., **198**: 542-552.

Russell, B.D., Harley, C.D., Wernberg, T., Mieszkowska, N., Widdicombe, S., Hall-Spencer, J.M. and Connell, S.D. 2012. Predicting ecosystem shifts requires new approaches that integrate the effects of climate change across entire systems. Biology letters, **8**(2): 164-166.

Røjbek, C., Jacobsen, C., Tomkiewicz, J. and Støttrup, G. 2012. Linking lipid dynamics with the reproductive cycle in Baltic cod *Gadus morhua*. Mar. Ecol. Prog. Ser., **471**: 215-234. doi:10.3354/meps10012.

Sainte-Marie, B. 1993. Reproductive cycle and fecundity of primiparous and multiparous female snow crab, *Chionoecetes opilio*, in the northwest Gulf of Saint Lawrence. Can. J. Fish. Aquat. Sc., **50**(10): 2147-2156.

Sainte-Marie, B., Raymond, S. and Brêthes, J.C. 1995. Growth and maturation of the benthic stages of male snow crab, *Chionoecetes opilio* (Brachyura: Majidae). Can. J. Fish. Aquat. Sc., **52**(5): 903-924.

Sainte-Marie, B., Dufour, R., Bourassa, L., Chabot, D., Dionne, M., Gilbert, D., Rondeau, A. and Sévigny, J.-M. 2005. Criteria and proposition for the definition of snow crab (*Chionoecetes opilio*) production units in the Estuary and Northern Gulf of St. Lawrence. Can. Sc. Adv. Secr. Res. Doc. 2005/059: v + 20 p.

Sainte-Marie, B., Gosselin, T., Sévigny, J.M. and Urbani, N. 2008. The snow crab mating system: opportunity for natural and unnatural selection in a changing environment. Bull. Mar. Sci., **83**(1): 131-161.

Sartoris, F.J., Bock, C., Serendero, I., Lannig, G. and Pörtner, H.O. 2003. Temperature-dependent changes in energy metabolism, intracellular pH and blood oxygen tension in the Atlantic cod. J. Fish Biol., **62**(6): 1239-1253.

Savard, L. and Bourdages, H. 2012. Update of the estimation of northern shrimp *Pandalus borealis* biomass and abundance from the trawl survey in the Estuary and the northern Gulf of St. Lawrence in 2012. DFO Can. Sci. Advis. Sec. Res. Doc., **2012/004**: ii + 33.

Savenkoff, C., Grégoire, F. and Chabot, D. 2004. Main prey and predators of capelin (*Mallotus villosus*) in the northern and southern Gulf of St. Lawrence during the mid-1980s and mid-1990s. Can. Techn. Rep. Fish. Aquat. Sci. 2551: vi + 30 p. Available from http://www.dfo-mpo.gc.ca/Library/284157.pdf

Savenkoff, C., Grégoire, F., Castonguay, M., Swain, D.P., Chabot, D. and Hanson, J.M. 2005. Main prey and predators of Atlantic mackerel (*Scomber scombrus* L.) in the northern and southern Gulf of St Lawrence during the mid-1980s, mid-1990s, and early 2000s. Can. Techn. Rep. Fish. Aquat. Sci. 2619: v + 29 p. Available from http://www.dfo-mpo.gc.ca/Library/318638.pdf

Savenkoff, C., Castonguay, M., Chabot, D., Fréchet, A., Hammill, M.O. and Morissette, L. 2006a. Main prey and predators and estimates of mortality of Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence during the mid-1980s, mid-1990s, and early 2000s. Can. Techn. Rep. Fish. Aquat. Sci. 2666: vi + 32 p. Available from http://www.dfo-mpo.gc.ca/Library/325175.pdf

Savenkoff, C., Grégoire, F., Castonguay, M., Hanson, J.M., Chabot, D. and Swain, D. 2006b. Main prey and predators of Atlantic herring (*Clupea harengus* L.) in the Gulf of St. Lawrence during the mid-1980s, mid-1990s, and early 2000s. Can. Techn. Rep. Fish. Aquat. Sci. 2643: vi + 28 p. Available from http://www.dfo-mpo.gc.ca/Library/321212.pdf

Savenkoff, C., Morin, B., Chabot, D. and Castonguay, M. 2006c. Main prey and predators of redfish (*Sebastes* spp.) in the northern Gulf of St. Lawrence during the mid-1980s, mid-1990s, and early 2000s. Can. Techn. Rep. Fish. Aquat. Sci. 2648: vi + 23 p. Available from http://www.dfo-mpo.gc.ca/Library/322333.pdf

Savenkoff, C., Savard, L., Morin, B. and Chabot, D. 2006d. Main prey and predators of northern shrimp (*Pandalus borealis*) in the northern Gulf of St. Lawrence during the mid-1980s, mid-1990s, and early 2000s. Can. Techn. Rep. Fish. Aquat. Sci. 2639: v + 28 p. Available from http://www.dfo-mpo.gc.ca/Library/321701.pdf

Scattergood, L.W. and Tibbo, S.N. 1959. The herring fishery of the Northwest Atlantic. Bull. Fish. Res. Board Can.: vii + 42 p.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Can. J. Fish. Aquat. Sc., **58**(1): 18-29.

Schurmann, H. and Steffensen, J.F. 1992. Lethal oxygen levels at different temperatures and the preferred temperature during hypoxia of the Atlantic cod, *Gadus morhua* L. J. Fish Biol., **41**(6): 927-934.

Schurmann, H. and Steffensen, J.F. 1997. Effects of temperature, hypoxia and activity on the metabolism of juvenile Atlantic cod. J. Fish Biol., **50**(6): 1166-1180.

Scott, W.B. and Scott, M.G. 1988. Atlantic fishes of Canada. Can. Bull. Fish. Aquat. Sci., **219**: 1-731.

Sette, O.E. 1943. Biology of the Atlantic mackerel (*Scomber scombrus*) of North America Part I: Early life history, including the growth, drift, and mortality of the egg and larval populations. Fish. Bull., **50**(38): 149-237.

Sette, O.E. 1950. Biology of the Atlantic mackerel (*Scomber scombrus*) of North America Part II—Migrations and habits. Fish. Bull., **51**(49): 251-358.

Sévigny, J.-M., Roques, S., Bernatchez, L., Valentin, A., Parent, É., Black, M., Chanut, J.-P., Marcogliese, D., Arthur, R., Albert, E., Desrosiers, B. and Atkinson, B. 2003. Species identification and stock structure, pp. 13-46 *In* Redfish multidisciplinary research zonal program (1995-1998): Final report. *Edited by* D. Gascon. Can. Techn. Rep. Fish. Aquat. Sci. 2462: xiii + 139 p. Available from http://www.dfo-mpo.gc.ca/Library/274564.pdf

Sévigny, J.-M., Méthot, R., Bourdages, H., Power, D. and Comeau, P. 2007. Review of the structure, the abundance and distribution of *Sebastes mentella* and *S. fasciatus* in Atlantic Canada in a species-at-risk context: an update. Can. Sc. Adv. Secr. Res. Doc. 2007/085: x + 99 p. Available from http://www.dfo-mpo.gc.ca/CSAS/Csas/DocREC/2007/RES2007_085_e.pdf

Shackell, N. and Loder, J. 2012. Climate change and its effects on ecosystems, habitats and biota. State of the Scotian Shelf Report 3: 1-29 p. Available from http://coinatlantic.ca/docs/climate-change-and-its-effects-on-ecosystems-habitats-and-biota.pdf

Shackell, N.L., Bundy, A., Nye, J.A. and Link, J.S. 2012. Common large-scale responses to climate and fishing across Northwest Atlantic ecosystems. ICES J. Mar. Sci., **69**(2): 151-162.

Shumway, S.E., Perkins, H.C., Schick, D.F. and Stickney, A.P. 1985. Synopsis of biological data on the pink shrimp, *Pandalus borealis* Krøyer, 1838. NOAA Technical Report NMFS, **30**: iv + 57.

Simard, Y. and Savard, L. 1990. Variability, spatial patterns and scales of similarity in size-frequency distributions of the Northern Shrimp (*Pandalus borealis*) and its migrations in the Gulf of St. Lawrence. Can. J. Fish. Aquat. Sc., **47**(4): 794-804.

Simpson, S.D., Jennings, S., Johnson, M.P., Blanchard, J.L., Schön, P.-J., Sims, D.W. and Genner, M.J. 2011. Continental shelf-wide response of a fish assemblage to rapid warming of the sea. Curr. Biol., **21**(18): 1565-1570.

Smith, P.C., Black, M., Pettipas, R., Page, F. and Drinkwater, K. 2003. Redfish environmental associations and exposure histories, pp. 85-88 *In* Redfish multidisciplinary research zonal program (1995-1998): Final report. *Edited by* D. Gascon. Can. Techn. Rep. Fish. Aquat. Sci.: xiii + 139 p. Available from http://www.dfo-mpo.gc.ca/Library/274564.pdf

Squires, H.J. 1992. Recognition of *Pandalus eous* Makarov, 1935 as a Pacific species not a variety of the Atlantic *Pandalus borealis* Krøyer, 1838 (Decapoda, Caridea). Crustaceana, **63**.

Starr, M., Therriault, J.C., Conan, G.Y., Comeau, M. and Robichaud, G. 1994. Larval release in a sub-euphotic zone invertebrate triggered by sinking phytoplankton particles. J. Plankton Res., **16**(9): 1137-1147.

Stein, M. 2007. Warming periods off Greenland during 1800-2005: their potential influence on the abundance of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in Greenlandic waters . J. Northw. Atl. Fish. Sci., **39**: 1-20. doi:10.2960/J.v39.m580.

Stephenson, R.L., Clark, K.J., Power, M.J., Fife, F.J. and Melvin, G.D. 2001. Herring stock structure, stock discreteness, and biodiversity *In* Herring: Expectations for a new millenium. *Edited by* University of Alaska Sea Grant College Program Report, Anchorage, AK. pp. 559-571.

Stephenson, R.L., Melvin, G.D. and Power, M.J. 2009. Population integrity and connectivity in Northwest Atlantic herring: a review of assumptions and evidence. ICES J. Mar. Sci., **66**(8): 1733-1739. doi:10.1093/icesjms/fsp189.

Stewart, J.E., Cornick, J.W. and Zwicker, B.M. 1969. Influence of temperature on gaffkemia, a bacterial disease of the lobster *Homarus americanus*. J. Fish. Res. Board Can., **26**(9): 2503-2510.

Stobo, W.T. and Fowler, M. 2009. Herring tagging in the vicinity of the Scotian Shelf and Gulf of St. Lawrence by the Maritimes Region, 1973-1982. Can. Techn. Rep. Fish. Aquat. Sci. 2851: iv + 69 p. Available from http://www.dfo-mpo.gc.ca/Library/338016.pdf

Studholme, A.L., Packer, D.B., Berrien, P.L., Johnson, D.L., Zetlin, C.A. and Morse, W.W. 1999. Essential fish habitat source document: Atlantic mackerel, *Scomber scombrus*, life history and habitat characteristics. NOAA Technical Memorandum NMFS-NE-141: v + 35 p.

Swain, D.P. 1997. Sex-specific temperature distribution of American plaice (*Hippoglossoides platessoides*) and its relation to age and abundance. Can. J. Fish. Aquat. Sc., **54**(5): 1077-1087.

Swain, D.P. and Kramer, D.L. 1995. Annual variation in temperature selection by Atlantic cod *Gadus morhua* in the southern Gulf of St. Lawrence, Canada, and its relation to population size. Mar. Ecol. Prog. Ser., **116**(1): 11-23.

Swain, D.P. and Morin, R. 1997. Effects of age, sex and abundance on the bathymetric pattern of American plaice in the southern Gulf of St Lawrence. J. Fish Biol., **50**(1): 181-200.

Swain, D.P., Chouinard, G.A., Morin, R. and Drinkwater, K.F. 1998. Seasonal variation in the habitat associations of Atlantic cod (*Gadus morhua*) and American plaice (*Hippoglossoides platessoides*) from the southern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sc., **55**(12): 2548-2561.

Templeman, W. 1936. The influence of temperature, salinity, light and food conditions on the survival and growth of the larvae of the lobster (*Homarus americanus*). J. Biol. Board Can., **2**(5): 485-497.

ter Hofstede, R. and Rijnsdorp, A.D. 2011. Comparing demersal fish assemblages between periods of contrasting climate and fishing pressure. ICES J. Mar. Sci., **68**(6): 1189-1198.

Thorarensen, H., Gústavsson, A., Mallya, Y., Gunnarsson, S., Árnason, J., Arnarson, I., Jónsson, A.F., Smáradóttir, H., Zoega, G.T. and Imsland, A.K. 2010. The effect of oxygen saturation on the growth and feed conversion of Atlantic halibut (*Hippoglossus hippoglossus* L.). Aquaculture, **309**(1-4): 96-102. doi:10.1016/j.aquaculture.2010.08.019.

Tomkiewicz, J., Lehmann, K.M. and St. John, M.A. 1998. Oceanographic influences on the distribution of Baltic cod, *Gadus morhua*, during spawning in the Bornholm Basin of the Baltic Sea. Fish. Oceanogr., **7**(1): 48-62.

Tremblay, J., Pezzack, D., Denton, C., Reeves, A., Smith, S., Silva, A. and Allard, J. 2011. Framework for assessing lobster off the coast of eastern Cape Breton and the eastern and south shores of Nova Scotia (LFAs 27-33). Can. Sc. Adv. Secr. Res. Doc. 2011/058: viii + 180 p.

Tremblay, M.J. 1997. Snow crab (*Chionoecetes opilio*) distribution limits and abundance trends on the Scotian Shelf. J. Northw. Atl. Fish. Sci., **21**: 7-22.

Trenkel, V.M., Huse, G., MacKenzie, B.R., Alvarez, P., Arrizabalaga, H., Castonguay, M., Goñi, N., Grégoire, F., Hátún, H., Jansen, T., Jacobsen, J.A., Lehodey, P., Lutcavage, M., Mariani, P., Melvin, G.D., Neilson, J., Nøttestad, L., Óskarsson, G.J., Payne, M.R., Richardson, D.E., Senina, I. and Speirs, D.C. 2013. Comparative ecology of widely distributed pelagic fish species in the North Atlantic: implications for modelling climate and fisheries impacts. Prog. Oceanogr., **Submitted**.

Trippel, E.A. 1995. Age at maturity as a stress indicator in fisheries. Bioscience, **45**(11): 759-771.

Trzcinski, M.K., den Heyer, C., Armsworthy, S., Whoriskey, S., Archambault, D., Trebel, M., Simpson, M. and Mossman, J. 2011. Pre-COSEWIC review of Atlantic halibut (*Hippoglossus hippoglossus*) on the Scotian Shelf and Southern Grand Banks (Divs. 3NO)s4VWX5Zc), Gulf of St. Lawrence (Divs. 4RST), Newfoundland and Labrador, and Central and Arctic. Can. Sc. Adv. Secr. Res. Doc. 2011/030: vi + 77 p. Available from http://www.dfo-mpo.gc.ca/Csas-sccs/publications/resdocs-docrech/2011/2011_030-eng.pdf

Valentin, A. 2006. Structure des populations de sébaste de l'Atlantique du nord-ouest dans un contexte de gestion des stocks et d'évolution. Ph.D. thesis. Université du Québec à Rimouski, Rimouski, QC. xxiii + 212 pp.

van Keeken, O.A., van Hoppe, M., Grift, R.E. and Rijnsdorp, A.D. 2007. Changes in the spatial distribution of North Sea plaice (*Pleuronectes platessa*) and implications for fisheries management. J. Sea Res., **57**(2): 187-197.

Vesin, J.-P., Leggett, W.C. and Able, K.W. 1981. Feeding ecology of capelin (*Mallotus villosus*) in the estuary and western Gulf of St. Lawrence and its multispecies implications. Can. J. Fish. Aquat. Sc., **38**(3): 257-267.

Wahle, R.A., Gibson, M. and Fogarty, M. 2009. Distinguishing disease impacts from larval supply effects in a lobster fishery collapse. Mar. Ecol. Prog. Ser., **376**: 185-192.

Waiwood, K.G. and Buzeta, M.-I. 1989. Reproductive biology of southwest Scotian Shelf haddock (*Melanogrammus aeglefinus*). Can. J. Fish. Aquat. Sc., **46**(S1): s153-s170.

Waiwood, K. and Majkowski, J. 1984. Food consumption and diet composition of cod, *Gadus morhua*, inhabiting the southwestern Gulf of St. Lawrence. Environ. Biol. Fish., **11**: 63-78.

Walsh, S.J. 1994. Life history traits and spawning characteristics in populations of long rough dab (American plaice) *Hippoglossoides platessoides* (Fabricus) in the North Atlantic. Neth. J. Sea Res., **32**(3): 241-254.

Westin, L. and Nissling, A. 1991. Effects of salinity on spermatozoa motility, percentage of fertilized eggs and egg development of Baltic cod (*Gadus morhua*), and implications for cod stock fluctuations in the Baltic. Mar. Biol., **108**(1): 5-9.

Wieczorek, S.K. and Hooper, R.G. 1995. Relationship between diet and food availability in the snow crab *Chionoecetes opilio* (O. Fabricius) in Bonne Bay, Newfoundland. J. Crus. Biol., **15**(12): 236-247.

Wieland, K., Waller, U. and Schnack, D. 1994. Development of Baltic cod eggs at different levels of temperature and oxygen content. Dana, **10**: 163-177.

Wieland, K., Jarre-Teichmann, A. and Horbowa, K. 2000. Changes in the timing of spawning of Baltic cod: possible causes and implications for recruitment. ICES J. Mar. Sci., **57**(2): 452.

Wilson, R.E. and Swanson, R.L. 2005. A perspective on bottom water temperature anomalies in Long Island Sound during the 1999 lobster mortality event. J. Shellfish Res., **24**(3): 825-830.

Winters, G.H. and Wheeler, J.P. 1987. Recruitment dynamics of spring-spawning herring in the Northwest Atlantic. Can. J. Fish. Aquat. Sc., **44**(4): 882-900.

Worley, L.G. 1933. Development of the egg of the mackerel at different constant temperatures. New Journal, **16**(5): 841-857.

Worm, B. and Myers, R.A. 2003. Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. Ecology, **84**(1): 162-173.

Youcef, W.A., Lambert, Y. and Audet, C. 2013. Spatial distribution of Greenland halibut *Reinhardtius hippoglossoides* in relation to abundance and hypoxia in the estuary and Gulf of St. Lawrence. Fish. Oceanogr., **22**(1): 41-60. doi:10.1111/fog.12004.

Zheng, J. and Kruse, G.H. 2000. Recruitment patterns of Alaskan crabs in relation to decadal shifts in climate and physical oceanography. ICES J. Mar. Sci., **57**(2): 438-451.

Chapter 5 Life history, status and potential impacts of climate variability and change on Atlantic salmon with emphasis on eastern Canada

M.J. Robertson [1], J.B. Dempson [1], M.F. O'Connell [1], and G. Chaput [2]

[1] Northwest Atlantic Fisheries Centre, Fisheries and Oceans Canada, 80 East White Hills Road, P. O. Box 5667, St. John's, NL A1C 5X1

[2] Gulf Fisheries Centre, Fisheries and Oceans Canada, 343 Université Avenue, P. O. Box 5030, Moncton, NB E1C 9B6

*Correspondence: Martha.Robertson@dfo-mpo.gc.ca

Suggested Citation:

Robertson, M.J., J.B. Dempson, M.F. O'Connell, and G. Chaput. 2013. Life history, status and potential impacts of climate variability and change on Atlantic salmon with emphasis on eastern Canada. Ch. 5 (p. 169–194) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

5.1 SUMMARY

Aspects of the life history and ecology of Atlantic salmon (*Salmo salar*) are summarized with emphasis on characteristics that are known to be influenced by environmental conditions and hence potentially impacted by climate variability and change. In North America, salmon are distributed from the temperate regions of New England and the Maritimes to the subarctic areas of north Labrador and northern Québec. Within this range, anadromous salmon occupy freshwater and marine environments that have a diverse array of physical and biological characteristics. Thus, salmon populations are expected to vary substantially in their response to climate change. The most severe impacts will likely occur in southern areas where populations could disappear. Salmon rivers at the northern edge of the range are expected to become more productive and colonization northward may be possible. The timing and/or duration of various salmon life-history stages (i.e., migrations, spawning, hatching, and smolting) will be affected by increased water temperatures and changes in spring freshwater discharge.

These changes will likely be maladaptive and negatively affect Atlantic salmon production. In general, existing information predicts an overall depletion of salmon throughout its range as a result of warmer/drier summers in the south, warmer winters in the north, and increased mortality from parasites and diseases.

5.2 INTRODUCTION

In many areas of the north Atlantic populations of Atlantic salmon (*Salmo salar*) are either in a state of decline or now extirpated such that concern over the continued survival of the species has been given much attention (Parrish et al. 1998; Potter and Crozier 2000; Hutchinson et al. 2002; Jonsson and Jonsson 2004a; Horreo et al. 2011; Chaput 2012). Other populations, while stable, have shown little or no improvement. In the past, high rates of exploitation in ocean fisheries were often associated with many stock declines and seen as a serious threat to the future conservation of salmon (Mills 1993, 2000). Marine exploitation rates ranged from 70 to 90% on multi-sea-winter (MSW) components, while one-sea-winter (1SW) stocks were harvested at 40 to 60% (e.g., Hansen 1988, 1990; Crozier and Kennedy 1994; Dempson et al. 2001). Consequently, management measures were often introduced to reduce and later eliminate much of the directed ocean exploitation on salmon. Yet, Atlantic salmon abundance continued to decline in many areas despite the absence of, or great reduction in, ocean fisheries (Ritter 1993; Parrish et al. 1998; Chase 2003; Friedland et al. 2003; Dempson et al. 2004; Robertson et al. 2010). Declines in salmon returns to home waters have been greater for MSW salmon by comparison with the 1SW life stage (e.g., Chaput 2012).

Definitive reasons for the decline in salmon abundance remain unknown but are likely many and varied (e.g., Parrish et al. 1998; Cairns 2001; Jonsson and Jonsson 2004a). Factors could include, either in whole or in part, predation and disease (e.g., Amiro 1998; Montevecchi et al. 2002; Middlemas et al. 2003; Finstad et al. 2011a; Harris et al. 2011; Ward and Hvidsten 2011), impacts of cultured fish (e.g., Gausen and Moen 1991; Hutchinson 1997 and papers therein; Jonsson and Jonsson 2006; Ferguson et al. 2007), endocrine disrupting compounds or other contaminants (e.g., Zitko 1995; Fairchild et al. 1999; Rosseland and Kroglund 2011), and various factors associated with changes in freshwater and ocean climate and productivity (e.g., Gibson 1993, 2002; Minns et al. 1995; Friedland et al. 1998; Drinkwater 2000; Beaugrand and Reid 2003, 2012; Jonsson and Jonsson 2004a; Finstad et al. 2011b; Todd et al. 2011, 2012).

The following provides: (a) an overview of the life history and ecology of Atlantic Salmon, extracted largely from Klemetsen et al. (2003) and O'Connell et al. (2006), highlighting areas that are known to be influenced by environmental conditions, (b) current trends and status of salmon in Eastern Canada and (c) a summary of potential effects climate change may have on salmon populations drawing from recent overviews provided by Jonsson and Jonsson (2009) and Todd et al. (2011, 2012). Within the report references are made to rivers within the provinces of eastern Canada, Salmon Fishing Areas (SFAs), and fishing zones (Qs) for the Province of Quebéc (Fig. 5–1).

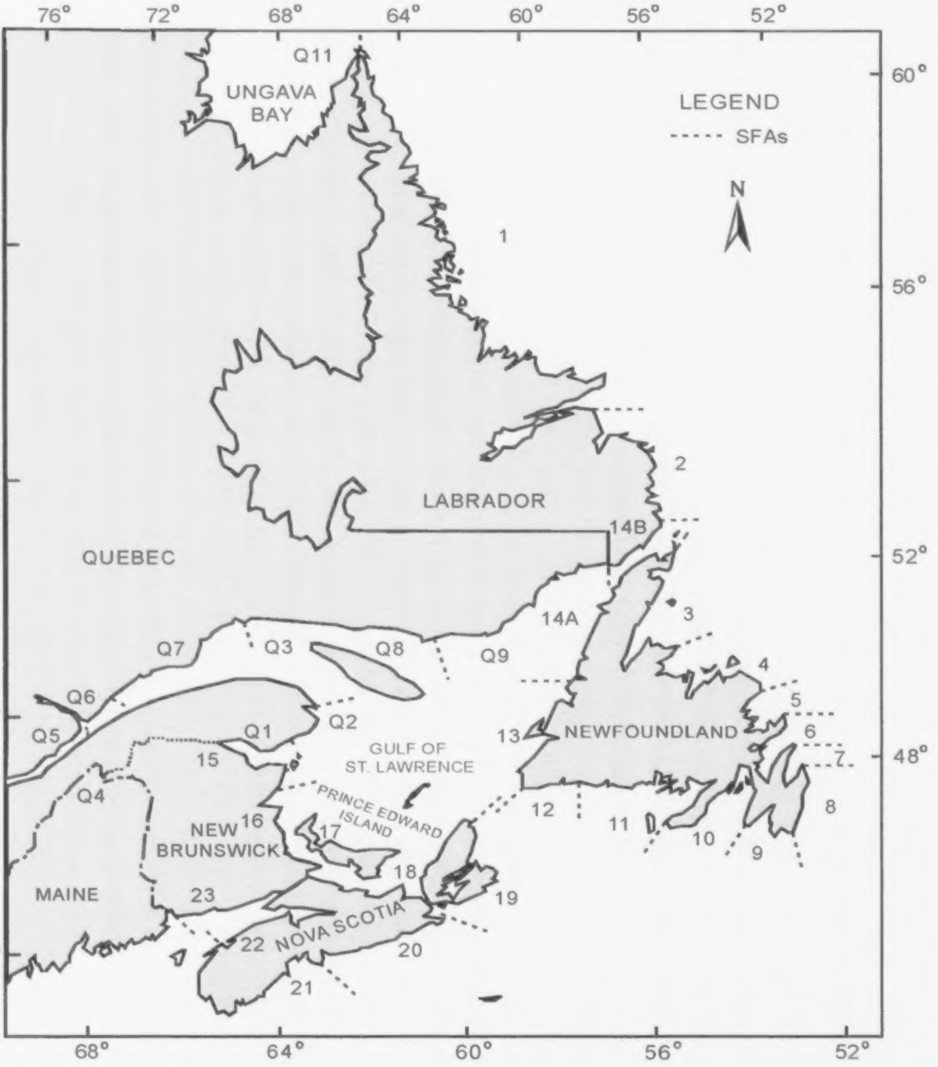
76°
72°
68°
64°
60°
56°
52°
60°
56°
52°
48°
56°
52°
48°
44°
Q11
UNGAVA BAY
LEGEND
----- SFAs
N
1
2
LABRADOR
14B
QUEBEC
3
14A
Q7
Q3
Q8
Q9
4
5
Q6
Q2
6
Q5
Q1
13
NEWFOUNDLAND
7
15
GULF OF ST. LAWRENCE
Q4
16
NEW BRUNSWICK
PRINCE EDWARD ISLAND
17
12
11
10
9
8
18
MAINE
23
19
22
NOVA SCOTIA
20
21
68°
64°
60°
56°
52°

Figure 5–1 Map showing the Salmon Fishing Areas (SFAs) of Newfoundland and Labrador, Nova Scotia, New Brunswick, and Prince Edward Island, and Management Zones (Qs) of Québec.

5.3 ATLANTIC SALMON LIFE HISTORY

Atlantic salmon occur naturally along both east and west coasts of the North Atlantic Ocean where it exists in both anadromous and non-anadromous freshwater resident forms. In the northwest Atlantic, salmon occur from approximately the Connecticut River in the south to Ungava Bay in the north (MacCrimmon and Gots 1979) occupying a diverse array of physical and biological environments (Elliott et al. 1998). In the northeast Atlantic, salmon range from Portugal in the south to the Barents, White and Kara seas in the north (MacCrimmon and Gots 1979). Freshwater resident populations are common throughout the entire distributional range (Power 1958; MacCrimmon and Gots 1979). Both within and among populations, salmon display variability in freshwater habitat use (Gibson 1993; Heggenes et al. 1999), length of freshwater residence (Randall et al. 1987) and sea-age at maturity (Meerburg 1986; Power 1986; Randall et al. 1986; Riddell 1986; Jonsson et al. 1991).

Figure 5–2 is a generalized depiction of the salient features of the life cycle of Atlantic salmon. Atlantic salmon is an iteroparous species, one that can spawn repeatedly, as opposed to most species of Pacific salmon (*Oncorhynchus*), which are semelparous and die after a single spawning (Schaffer 1974; Fleming and Reynolds 2004). A defining characteristic of anadromous Atlantic salmon is the ability to return with a high degree of fidelity to the natal river or tributary for spawning (homing) (Stabell 1982, 1984; Hansen and Quinn 1998). Such precision in homing has led to the formation and maintenance of river-specific or local adaptations, resulting in much of the variability in genetic, life-history, behavioral, and other traits observed throughout the range of the species (Saunders and Schom 1985; Taylor 1991).

Depending on the stock, spawners returning to rivers are comprised of varying proportions of maiden fish (those spawning for the first time) and repeat spawners (Fig. 5–3). Most maiden salmon in turn consist of varying proportions of smaller fish that return to spawn after one winter at sea (1-sea-winter or 1SW) also known as grilse, and larger fish that return after two or more winters at sea (2, 3-sea-winter, also designated as multi-sea-winter or MSW) Some rivers possess a maiden salmon component that returns to spawn after only a few months at sea (0-sea-winter or 0SW). Throughout its entire range in North America, adult Atlantic salmon return to rivers from feeding and staging areas in the sea mainly between May and November, but some runs can begin as early as March and April. In general, run timing varies by river, sea age, year, and hydrographic conditions. Run timing is believed to be a heritable trait (Hansen and Jonsson 1991a) that is also influenced by environmental conditions such as water temperature, discharge and tides (Banks 1969; Jonsson 1991; Jonsson et al. 2007; Thorstad et al. 2008, 2011). For smolts, threshold temperatures for migration in the 7-10 °C range have been reported (Power 1981).

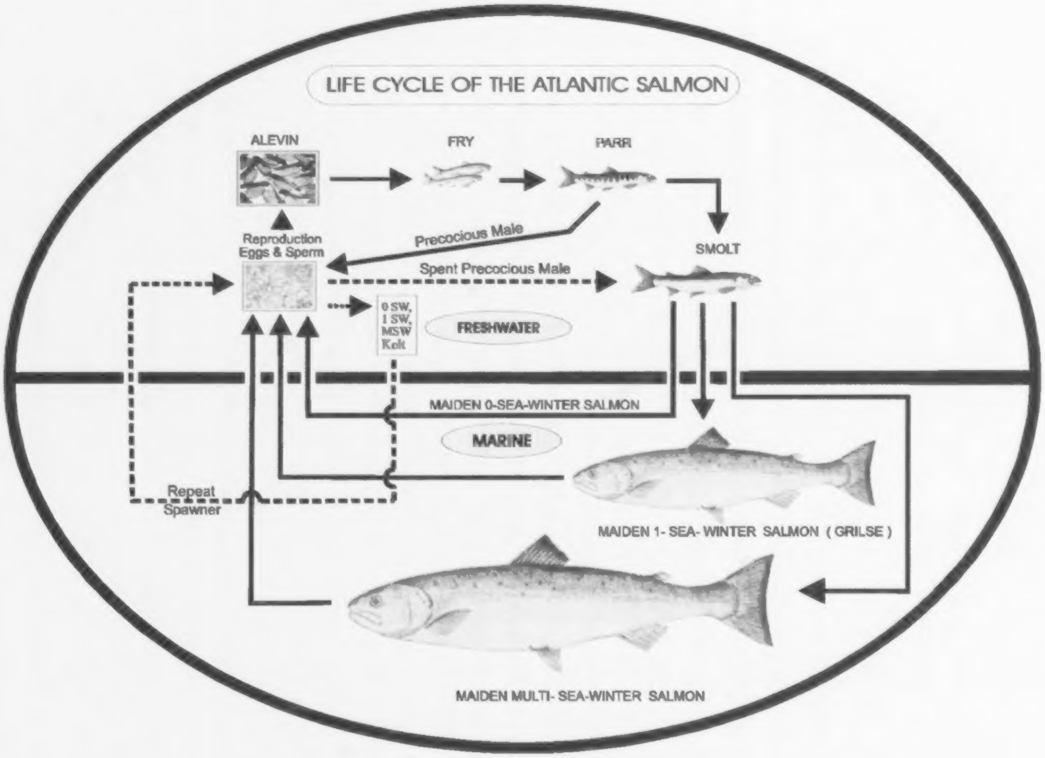
LIFE CYCLE OF THE ATLANTIC SALMON
ALEVIN
FRY
PARR
Reproduction
Eggs & Sperm
Precocious Male
SMOLT
Spent Precocious Male
0 SW,
1 SW,
MSW
Kelt
FRESHWATER
MAIDEN 0-SEA-WINTER SALMON
MARINE
Repeat
Spawner
MAIDEN 1- SEA- WINTER SALMON (GRILSE)
MAIDEN MULTI- SEA-WINTER SALMON

Figure 5–2 Generalized life cycle of the Atlantic Salmon.

Spawning usually occurs in October and November in gravel-bottomed riffle areas of streams. Fertilization of eggs can involve both adult males and mature juvenile males (precocious parr). Spawned-out or spent fish (kelts) either return to sea immediately after spawning or remain in freshwater until the following spring. Eggs incubate in the spawning nests (redds) over the winter months and hatching usually begins in April. The hatchlings (alevins) remain in the gravel for several weeks living off large yolk sacs. Upon emergence from the gravel in late May – early June, the yolk sac is absorbed and the free-swimming young fish (fry or under-yearling parr) begin active feeding. Juvenile fish (parr) rear in fluvial (riverine) and lacustrine (standing water) habitats for two to eight years after which time they enter the smolt stage and migrate to sea (Klemetsen et al. 2003). Hence, water temperatures, precipitation and discharge potentially influence aspects of the reproductive ecology of the species.

Relative proportions of the various maiden sea-ages, repeat spawners, and associated biological characteristics vary widely among stocks and with geographic locations in North America (Porter et al. 1986). For example, stock composition can vary from being comprised of three sea ages, such as those on the Gaspé Peninsula, to consisting of a single sea age, which is characteristic of most of Newfoundland rivers (Fig. 5–3). Sea-age at maturity has been associated with post-smolt growth rates and environmental conditions (Friedland and Haas 1996; Friedland et al. 1998; Jonsson and Jonsson 2004b).

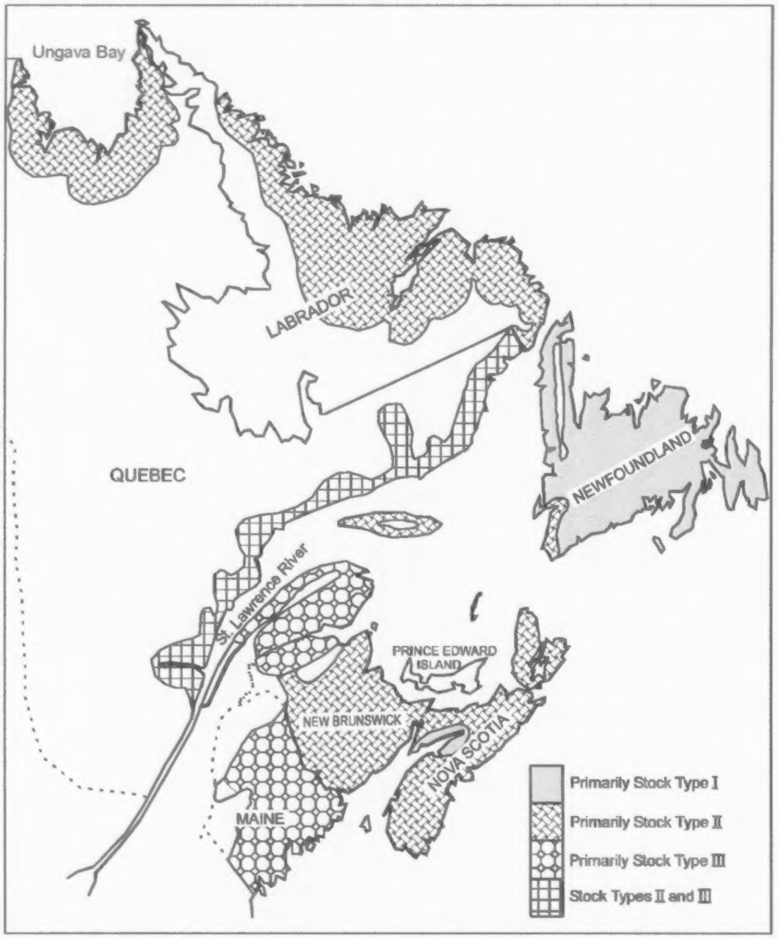
Ungava Bay
LABRADOR
QUEBEC
NEWFOUNDLAND
St. Lawrence River
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
MAINE
Primarily Stock Type I
Primarily Stock Type II
Primarily Stock Type III
Stock Types II and III

Figure 5–3 Distribution of generalized groupings of stock types of self-sustaining populations of Atlantic Salmon in North America. Stock Type I consists mainly of 1SW spawners, Type II has 1SW and 2SW spawners, and Type III is comprised of 1SW, 2SW, and 3SW spawners. Within each stock type area there may be a few stocks which belong to another stock type. Adapted from Porter et al. (1986).

In Ungava Bay (Q11, Fig. 5–1), at the northern extremity of the North American distribution, a form referred to as “estuarine” salmon occurs in addition to 1SW and MSW salmon (Robitaille et al. 1986). Unlike 1SW and older salmon, which undergo extensive oceanic migrations (Hansen and Quinn 1998), these fish can reach maturity and return to freshwater after only a few months in the estuary and are referred to as 0-sea-winter (0SW) salmon in Figure 5–2. While this form has also been encountered sporadically over the years in low numbers in Newfoundland, it has become more prevalent in recent years in certain rivers (Downton et al. 2001). Power (1981) has reported that both river and sea temperatures can confine the migration of Ungava salmon to a short interval thus affecting the life-cycle and maturation patterns.

5.3.1 Size and Growth in Freshwater

5.3.1.1 Juvenile (Parr)

Atlantic salmon inhabit cool temperate streams and can generally tolerate freshwater temperatures ranging from 0 to 28 °C (Elliott 1991). Juvenile Atlantic salmon begin feeding in the spring at water temperatures of 6 to 7 °C, and grow optimally at 16 to 19 °C (Javaid and Anderson 1967; Gibson 1978; Dwyer and Piper 1987; Jensen et al. 1989; Peterson and Martin-Robichaud 1989; Elliott, 1991; Elliott and Hurley 1997). Feeding ceases in larger juveniles at temperatures above 23 °C and at water temperatures ranging from 22 to 24 °C juvenile salmon seek refuge from thermal stress (Cunjak et al. 1993) moving to areas with cool water sources (Breau et al. 2007). Incipient and ultimate lethal temperatures of parr and smolt range from 22-28 °C, and 30-33 °C, respectively (Elliott 1991; Elliott and Elliott 2010) while freezing temperatures of salmon have been reported as -0.76 °C (Fletcher et al. 1988). Factors with the strongest correlation to body size and growth of juvenile salmon in freshwater include temperature, food availability and density (Gibson 1993; Elliott and Hurley 1997; Grant et al. 1998; Forseth et al. 2011). Several studies have reported on the short growing season of wild Atlantic salmon such that size at age is reached earlier in the year than would be expected based on temperature alone (Randall and Paim 1982; Metcalfe 1994; Elliott and Hurley 1997; Strothotte et al. 2005).

Salmon use both stream (fluvial) and lakes (lacustrine) for rearing with the latter particularly common in Newfoundland (Pepper et al. 1985; Hutchings 1986; O'Connell and Ash 1989, 1993; O'Connell and Dempson 1996; Gibson 2002). Habitats other than fluvial, including lacustrine, have been considered as marginal or secondary for juvenile anadromous salmon, occupied by individuals displaced from preferred stream habitat (Pepper et al. 1985; Gibson 1993), which is consistent with the traditional view that salmon are primarily stream dwellers (Keenleyside 1962; Gibson 1988, 1993; Marschall et al. 1998). The widespread use of lacustrine habitat by parr in Newfoundland is believed to be due to the relative lack of predators and competitors (Hutchings 1986; Gibson 1993; Gibson et al. 1993). Hutchings (1986) considered the use of lacustrine habitat to be non-random and resultant enhanced growth and survival relative to fluvial habitat to be of adaptive significance. It is also possible that ponds could serve as temporary refugia during periods of warm water conditions as observed in west coast population of sockeye salmon (Mathes et al. 2010).

5.3.1.2 Smolt

The proportion at smolt age from adult returns has been used to describe the smolt age characteristics of rivers in eastern Canada. While exceptions occur, there is a general tendency for smolt age to increase with latitude in wild North American populations (Power 1981) (Fig. 5–4). Maritime populations often have mean smolt ages between 2 and 3 years (see summary by Hutchings and Jones 1998); which is similar to populations in southwest Newfoundland. In contrast, most of Newfoundland has salmon populations characterized by mean smolt ages between 3 and 4 years, similar to many Québec stocks. Populations with mean smolt age of 4 or more years occur along the northwest coast of Newfoundland and into southern Labrador while mean smolt age in some northern Labrador, Québec and Ungava Bay stocks exceeds 5 years (Power 1969). Much of the variability has been explained by opportunities for growth that are influenced by local environmental characteristics (combination of degree-days and day length) (Power 1986; Metcalfe and Thorpe 1990). The probability of smoltification at a given age increases if a threshold size or growth rate is achieved by a critical time in the life cycle (Thorpe et al. 1998). As a consequence, small changes in initial growth rates of a cohort can affect the mean age at smoltification.

Wild smolts from some Bay of Fundy rivers are large relative to other MSW stocks, averaging between 14 and 16 cm fork length. The lengths of smolts from the Gulf of St. Lawrence rivers extending from the western side of Cape Breton Island (SFA 18) to the north shore of the St. Lawrence (Q7) have ranged between 12 and 14 cm with the smallest overall sizes in the St-Jean River on the Gaspe peninsula (Q2). Smolts are also longer at age in the southern stocks of SFA 23, ranging from 14 to 16 cm for 2-year-old smolts and 15.5 to over 18 cm for 3-year-old smolts. The highest mean smolt lengths are recorded from Ungava Bay at 21.5 cm (Power 1969).

In Newfoundland, length varies from approximately 12 to 15 cm in the fluvial systems (rivers comprised mainly of fluvial habitat) on the southwestern portion of the island. For the remainder of Newfoundland (1SW stocks), mean smolt length ranges from around 15 to 18 cm. O'Connell and Ash (1993) showed smolt size systems dominated by lacustrine habitat to be higher than for fluvial systems.

With the exception of Newfoundland, there is a tendency for smolt length to increase with latitude (data summarized in Hutchings and Jones 1998). The departure from the clinal tendency exhibited by Newfoundland populations is an example of the modifying effects of local environmental conditions on growth, in this case most likely the utilization of lacustrine habitat for rearing.

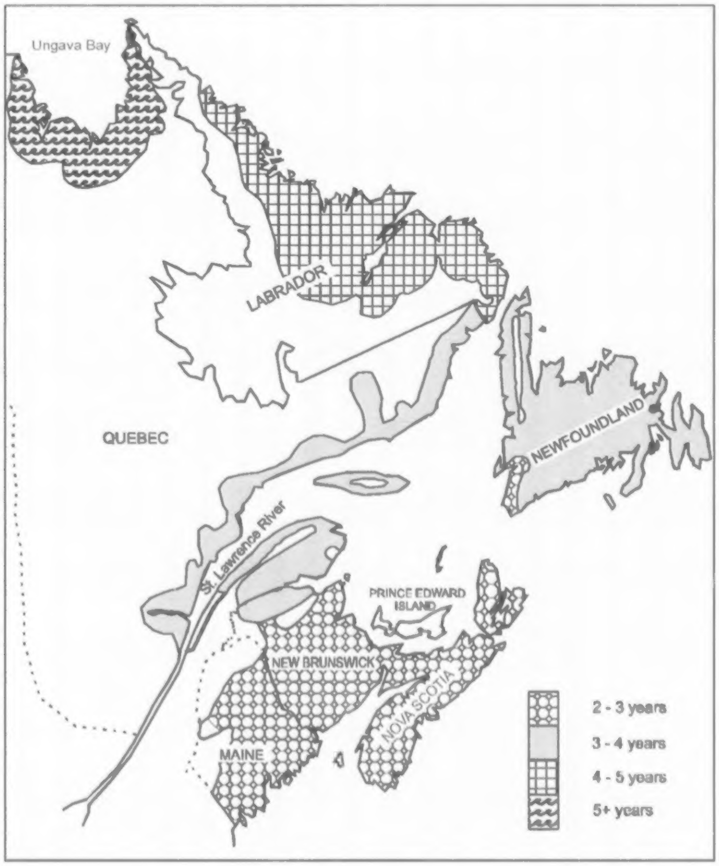
Ungava Bay
LABRADOR
QUEBEC
NEWFOUNDLAND
St. Lawrence River
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
MAINE
2 - 3 years
3 - 4 years
4 - 5 years
5+ years

Figure 5–4 Distribution of generalized stock groupings by smolt (river) age of self-sustaining populations of Atlantic Salmon in North America. Within each zone, exceptions to the generalization may occur.

5.3.2 Size and growth at sea

Atlantic salmon management in eastern Canada is based on two size groups defined by fork length; small salmon < 63 cm and large salmon ≥ 63 cm. Salmon return to rivers of eastern Canada to spawn predominantly after one, two, and in some areas three years at sea. In most regions, 1SW salmon are the most abundant maiden age group, sometimes representing almost 100% of maiden spawners in rivers of insular Newfoundland (Fig. 5–3). Two-sea-winter salmon are abundant in most rivers of the mainland of eastern Canada, especially in the southern Gulf of St. Lawrence, and are found in rivers on the southwest coast of Newfoundland (SFA 13) and in Labrador. Three-sea-winter salmon are infrequent other than in rivers of the southwestern Gulf of St. Lawrence (Baie des Chaleurs – SFA 15, Q1, Q2), and in some rivers of the north shore of the St. Lawrence (Q8); they have occurred historically in the Saint John River (SFA 23) and St. Mary's River (SFA 20). With few exceptions, small salmon are comprised of 1SW maiden fish whereas the large salmon category is comprised of multiple maiden age groups and repeat spawners.

The observed differences in the proportions at sea-age at maturity in the anadromous salmon of eastern Canada suggest that this trait reflects an adaptation of the populations to spatially variable conditions (Hutchings and Jones 1998). Factors which are considered to be important determinants of sea-age at maturity, and hence size, include growth rates (in freshwater and at sea), probability of survival in freshwater and at sea, fecundity, and heritability (Meerburg 1986; Chadwick et al. 1987; Friedland and Haas 1996; Hutchings and Jones 1998). Marine temperature has been shown to have a strong influence on growth of salmon at sea with subsequent consequences for survival and abundance (e.g., Friedland et al. 1993, 2000, 2003, 2009; Peyronnet et al. 2007, 2008).

Growth in the marine environment is rapid relative to that in freshwater. It takes two to four years for smolts to attain an average fork length of 12 to 18 cm in freshwater and only one year at sea to reach 45 to 65 cm. After two years at sea, salmon can be as large as 70 to 80 cm. Weights increase about 75-fold between the smolt stage and 1SW stage, and over 200-fold from smolts to 2SW salmon (Cairns 2003).

Size at maiden age varies among rivers. One-sea-winter maiden salmon mean lengths range between 48 and 59 cm. There does not seem to be any consistent pattern regarding size of 1SW salmon and latitude. Indeed larger 1SW salmon, ≥ 55 cm, can be found among populations from the Maritimes, Québec, and Newfoundland and Labrador with 1SW salmon averaging greater than 60 cm in some Ungava Bay rivers (Power 1969; Hutchings and Jones 1998). Two-sea-winter salmon mean lengths range from just over 60 cm in some rivers of the south coast of Newfoundland to between 75 and 80 cm in most other rivers. Three-sea-winter salmon mean lengths vary between 75 cm to over 100 cm.

5.4 TRENDS AND STATUS OF ATLANTIC SALMON

An overview of the trends and status of Canadian Atlantic Salmon populations was completed by the Committee on the Status of Endangered Wildlife in Canada in 2010 (COSEWIC 2010). Sixteen (16) population complexes, deemed 'designatable units' (DUs) were considered including the already extinct population of salmon in Lake Ontario. Four DUs were classed as 'Special Concern' including: Québec Eastern, Western North Shore, Inner St. Lawrence, and the Gaspe-Southern Gulf of St. Lawrence complex. The South Newfoundland DU was classed as 'Threatened'. Five DUs were classed as 'Endangered' including: Anticosti Island, Eastern Cape Breton, Nova Scotia Southern Upland (Gibson et al. 2011), and both the Inner and Outer Bay of Fundy. Labrador and the rest of Newfoundland were considered 'Not at Risk' while data were insufficient to evaluate the Nunavik DU (COSEWIC 2010).

Inferences related to trends in abundance of Atlantic Salmon on broad geographic scales are updated annually for ICES (ICES 2012)(Fig. 5–5).

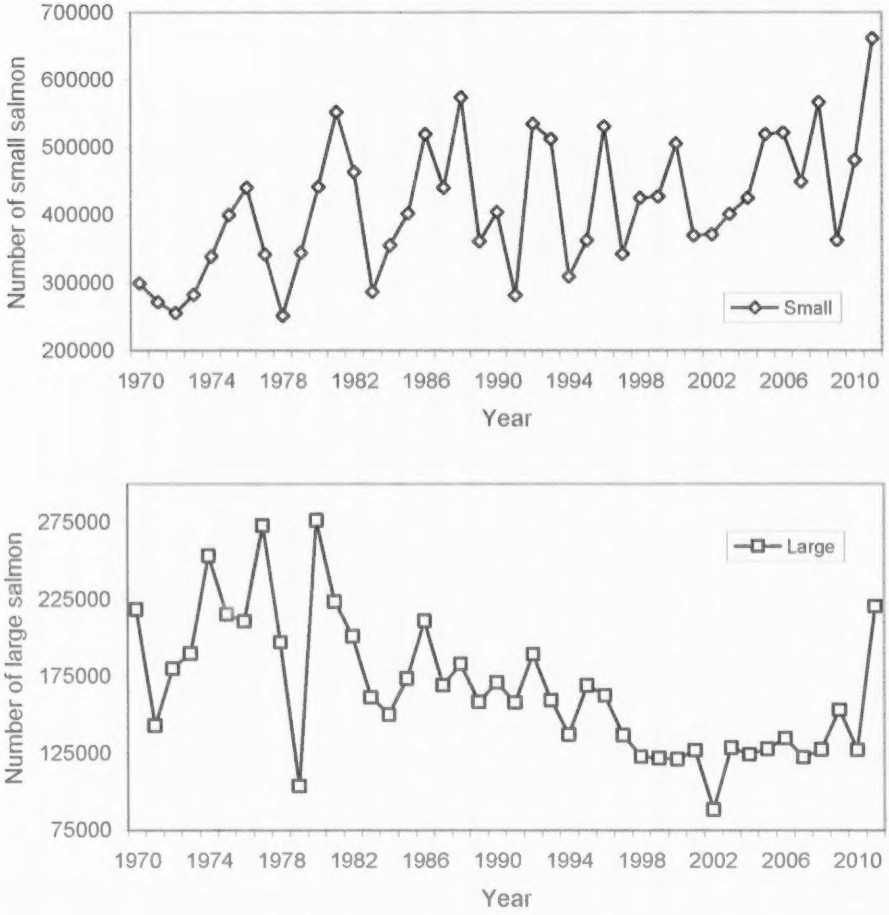

Figure 5–5 Trends in abundance of small (< 63 cm, upper panel) and large (≥ 63 cm, lower panel) Atlantic Salmon for North America, 1969–2011. Data obtained from ICES 2012.

Assessments are derived from run-reconstruction models (Potter et al. 2004) to estimate total population size prior to any mixed-stock fisheries (pre-fishery abundance PFA), such as at West Greenland, as well as estimates of returns and spawners (Chaput et al. 2005; Chaput 2012). Estimates of PFA of North American origin salmon have reportedly declined from about 2.3 million salmon during the early 1970s to less than 900 thousand fish in recent years (Chaput 2012). Within North America, estimates of returns to rivers of MSW salmon have declined by 81% over the period 1971-2009, while 1SW returns declined by 40% (1971-2010) (Chaput 2012). In contrast, numbers of spawners have increased for both MSW and particularly 1SW life stages.

However, as observed with the COSEWIC evaluation, trends in returns or numbers of spawners are not consistent across regions. Labrador and the island of Newfoundland have generally shown increases, while returns and spawners have declined in the Gulf, and particularly the Scotia-Fundy region. For the latter area, returns of 1SW and MSW fish have fallen by more than 80% over the period 1971-2010 (2009 for MSW fish), while spawning escapements of 1SW and MSW salmon have decreased by 75% and 89% respectively (Chaput 2012). The Québec region has had mixed results with 1SW returns and spawners increasing whereas MSW salmon have declined (Chaput 2012). Thus, as similarly observed in Europe, salmon populations in southern areas of North America have shown the greatest declines.

The most recent review (ICES 2012) has shown that both small and 2SW salmon returns in Labrador for 2011 were among the highest recorded but 2SW returns and spawners remain well below recommended conservation limits. For Newfoundland, estimated returns of small and 2SW salmon have continued to show an increasing trend with both components higher than previous 5-year means (ICES 2012).

Current information for Québec indicates both small and 2SW returns and spawners in 2011 were higher than previous 5-year means while 2SW spawners are still largely below recommended conservation limits (ICES 2012). In the Gulf of St. Lawrence small and 2SW returns and spawners for 2011 were both greater than previous 5-year means but 2SW spawners have generally been below conservation.

Farther south, the Scotia-Fundy region returns of small and 2SW salmon remain low and well below historic values (ICES 2012) with 2SW spawners continuing to be substantially less than conservation limits. In particular, populations in eastern Cape Breton, the Southern Upland area and the outer Bay of Fundy continue to do poorly with most monitored populations failing to meet conservation objectives (DFO 2012).

5.5 CLIMATE CHANGE IMPACTS TO ANADROMOUS ATLANTIC SALMON

Generalized climate change scenarios for North America suggest that winters will be milder and wetter, summers will be warmer and dryer, and the frequency of extreme weather events will increase (Jonsson and Jonsson 2009; Todd et al. 2011). Significant increases in annual mean temperatures have already occurred at time scales of 30 to 110 years, with more pronounced changes over the past 30 years (Thistle and Caissie 2013). Given the strong correlation between air and water temperatures, predicted increases in air temperature are expected to raise stream temperatures (Swansburg et al. 2004; Caissie 2006; Caissie 2012; Thistle and Caissie 2013). Total winter, spring and autumn precipitation has increased over the past 110 years in all Atlantic Canada but results are more variable at shorter time scales (Thistle and Caissie 2013). In most of eastern Canada, changes in streamflow characteristics over the previous 60 years include earlier spring maximum flows (freshets) and lower summer minimum flows (drought) that occur over longer durations (Thistle and Caissie 2013).

Predicted changes in freshwater, estuarine and marine environments will negatively affect the quality and quantity of habitat for anadromous fish species at various life-history stages and the resulting total impact to these species will likely be very significant (Minns et al. 1995; Reist et al. 2006). The impact of climate change on salmonid species has been the subject of recent reviews (Reist et al. 2006; Jonsson and Jonsson 2009; Todd et al. 2011)

5.5.1 Physiology

Atlantic salmon are cold tolerant and have the ability to store and maintain energy reserves necessary to survive long winter seasons (Cunjak et al 1998; Finstad et al. 2010). They have been observed avoiding warm groundwater areas in winter (5–7 °C) as it would increase metabolism and require feeding and assimilation rates for which they are not adapted (Cunjak 1996). Ice-free conditions have also been shown to deplete energy reserves in Atlantic salmon adapted to ice-covered habitats in winter (Hedger et al. 2013). Warmer winter conditions in northern rivers as a result of climate change are expected to reduce overwinter survival rates of Atlantic salmon.

In southern latitudes, higher summer water temperatures and lower minimum flows (drought) as a result of climate change will negatively affect Atlantic salmon production by limiting the amount of suitable habitat, increasing habitat fragmentation, and reducing egg and parr survival (Swansburg et al. 2002; King et al. 2003; Mather et al. 2008; Jonsson and Jonsson 2009; Clews et al. 2010). Higher water temperatures affect egg survival either directly in the redd when temperatures exceed thermal tolerance (Elliott and Elliott 2010) or by reducing egg quality in exposed females prior to spawning (King et al. 2003). In temperate and northern latitudes, the projected increase in spring and summer freshwater temperatures over longer durations will increase growth rates and the production of smolts, although at a younger age and smaller size (Minns et al. 1995; Jonsson et al. 2005; Jonsson and Jonsson 2009). Benefits of increased freshwater production may be outweighed by decreased marine survival of smaller smolts (Salminen et al. 1995; Jonsson et al. 2003; Russell et al. 2012).

Projected increases in sea surface temperatures are also expected to reduce post-smolt growth, survival, recruitment and the condition of maturing adults (Jonsson and Jonsson 2003; Condron et al. 2005; Todd et al. 2008; Jonsson and Jonsson 2009; Friedland and Todd 2012) especially in intermediate and southern areas. Age at maturity is also expected to decline and result in a reduction of MSW salmon (Jonsson and Jonsson 2004b).

Warmer temperatures in both freshwater and marine environments are expected to increase fish mortality from parasites and infectious diseases. This may occur as a result of more virulent strains, higher prevalence, increased transmission rates and reduced resistance due to stress (Marcogliese 2001, 2008; Karvonen et al. 2010; Pulkkinen et al. 2010).

5.5.2 Species Distribution

The distribution of Atlantic salmon has been shaped by post-glacial colonization routes, access to suitable habitats, climate and environmental conditions of which temperature is of prime importance (Power 1990). Gradual warming of the climate in the early 1900s was believed to be responsible for salmon expanding their range into the Kara Sea area of northwest Russia, east of the White Sea (MacCrimmon and Gots 1979). The presence and expanded harvest of Atlantic salmon along the coast of West Greenland has also been linked to ameliorating climate conditions in the early 1900s (Dunbar 1972; Dunbar and Thomson 1979). With increasing temperatures predicted as a result of climate change, the distribution of salmon may move farther northward (Power 1990; McCarthy and Houlihan 1997; Reist et al. 2006; Jonsson and Jonsson 2009; Todd et al. 2011). At the same time, populations along the southern extremes of their distribution will likely be extirpated as a result of severe drought conditions limiting available habitat and suitable water temperatures as lethal limits are more frequently exceeded (McCarthy and Houlihan 1997; Graham and Harrod 2009; Todd et al. 2011).

5.5.3 Timing of Seasonal Events (Phenology)

Climate warming is expected to result in changes in phenological events in salmon life history such as timing of the return migration to freshwater from the sea, time of spawning, subsequent hatching and emergence of young fish, and the timing of smolt migrations to sea.

With increasing temperatures, return migrations may be earlier (Jonsson and Jonsson 2009). In conjunction with lower summer precipitation this may be beneficial as salmon could enter rivers when flow conditions are still adequate and prior to periods of extended warm temperatures and low summer flows. On the other hand, drought conditions that result in low water levels may act to delay upstream migrations possibly resulting in higher stray rates to other rivers (Jonsson and Jonsson 2009) with some fish experiencing a loss of physiological opportunity to enter freshwater (Solomon and Sambrook 2004). Unusually high water levels may also act to delay upstream migrations (Jonsson and Jonsson 2009). Changes to earlier adult salmon run timing have already been observed in some North American populations where median date of return of some populations is progressively becoming earlier at a rate of about 0.5—0.9 d y^{-1} (Juanes et al. 2004).

Spawning time of salmon could be later as climate warms (Jonsson and Jonsson 2009). If warmer temperatures are coupled with decreased river flows salmon may be delayed or even prevented from accessing certain parts of smaller watersheds (Banks 1969; Thorstad et al. 2008; Todd et al. 2011). At the same time, increased temperatures may result in earlier hatch of eggs and subsequent emergence of alevins. Smolt migrations are strongly influenced by water temperature and photoperiod (Jonsson and Jonsson 2009) with run timing presumed to be adapted to local environmental conditions (McCormick et al. 1998). Warming temperatures have already resulted in earlier smolt migrations to sea (Kennedy and Crozier 2010; Russell et al. 2012; Otero et al. 2014) that could result in a mismatch with optimal conditions in the marine environment. This mismatch could have physiological as well as ecological consequences. Ecologically, smolt migrations are timed to take advantage of ample marine resources. If runs are too early, or too late, subsequent growth and survival of smolts may be impacted if type and abundance of suitable prey are not readily available (Rikardsen and Dempson 2011). Similarly, there is also an opportune "window" that renders smolts physiologically capable of adapting to the osmoregulatory demands of living in a high saline environment (Jonsson and Jonsson 2009; Thorstad et al. 2011; Todd et al. 2011). Survival of smolts and their ability to home to natal rivers may be compromised if the migration window is missed (Hansen and Jonsson 1991b; McCormick et al. 1998).

5.5.4 Chemistry

Increasing concentrations of CO_2 are believed to be contributing to global warming and the acidification of oceans (Orr et al. 2005; Fabry et al. 2008). Decreasing pH will affect those organisms that produce calcareous skeletal structures and impact zooplankton abundance and food web dynamics with potential implications for pelagic-feeding fish, such as salmon (Fabry et al. 2008; Dixon et al. 2012; Nielsen et al. 2013).

An additional consequence of warming conditions in rivers relates to the greater chance of juvenile salmon encountering lower oxygen conditions (Jonsson and Jonsson 2009). Earlier hatching is possible when eggs are stressed due to a lack of oxygen (Hamor and Garside 1976; Jonsson and Jonsson 2009). Reduced oxygen levels as a result of high water temperatures and low flow can lead to egg mortality and restrict recruitment (Jonsson and Jonsson 2009).

5.6 CONCLUSION: ANTICIPATED CONSEQUENCES TO FISHERIES AND OCEANS CANADA (DFO) PROGRAMS FROM ATLANTIC SALMON AS A RESOURCE

Atlantic salmon in Eastern Canada are managed on the basis of ensuring an adequate number of spawners in individual rivers (i.e., fixed escapement to meet conservation requirements) (O'Connell et al. 1997). Recreational fisheries on scheduled Atlantic salmon rivers are managed using daily, seasonal and size retention limits, seasons, and gear restrictions. Changes in the Atlantic salmon resource as a result of climate change include further overall depletion of the resource, shifts in the timing and/or duration of life-history stages (i.e., migrations, spawning, hatching, smolting) and possible expansion into northern areas. Fisheries management strategies for recreational and Aboriginal Atlantic salmon fisheries as well as fisheries where the by-catch of salmon could be significant (e.g., herring and mackerel) will need to adapt to these changes.

5.7 REFERENCES

Amiro, P. G. 1998. The abundance of harp seals in the north Atlantic and recruitment of the North American stock of Atlantic salmon (*Salmo salar*). Fisheries and Oceans Canada Canadian Stock Assessment Secretariat Research Document 98/84. 17 pp.

Banks, J. W. 1969. A review of the literature on the upstream migration of adult salmonids. Journal of Fish Biology 1: 85-136.

Beaugrand, G. and Reid, P. C. 2003. Long term changes in phytoplankton, zooplankton and salmon relate to climate. Global Change Biology 9: 801-817.

Beaugrand, G. and Reid, P. C. 2012. Relationships between North Atlantic salmon, plankton, and hydroclimatic change in the Northeast Atlantic. ICES Journal of Marine Science 69: 1549-1562.

Breau, C., Cunjak, R. A. and Bremset, G. 2007. Age-specific aggregation of wild juvenile Atlantic salmon *Salmo salar* at cool water sources during high temperature events. Journal of Fish Biology 71: 1179-1191.

Cairns, D. K. 2001. An evaluation of possible causes of the decline in pre-fishery abundance of North American Atlantic salmon. Canadian Technical Report of Fisheries and Aquatic Sciences No. 2358. 67 pp.

Cairns, D. K. 2003. Feeding, fasting, and weight-based estimation of natural mortality inmarine-phase Atlantic salmon (*Salmo salar* L.). In Marine mortality of Atlantic salmon, *Salmo salar* L: methods and measures, pp. 162-197. Potter, E.C.E., N. Ó Maoiléidigh,and G. Chaput [eds.] Department of Fisheries and Oceans Canadian Science Advisory Secretariat Research Document 2003/101. 213 pp.

Caissie, D. 2006. The thermal regime of rivers: a review. Freshwater Biology 51: 1389-1406.

Caissie, D. 2012. Impact of climate change on river water temperature and aquatic Resources. Document prepared for: DFO's Adaptation to Climate Change Aquatic Science Program (ACCASP).

Chadwick, E.M.P., Claytor, R. R., Léger C. E. and Saunders, R. L. 1987. Inverse correlation between ovarian development of Atlantic salmon (*Salmo salar*) smolts and sea age. Canadian Journal of Fisheries and Aquatic Sciences 44: 1320-1325.

Chaput, G. 2012. Overview of the status of Atlantic salmon (*Salmo salar*) in the North Atlantic and trends in marine mortality. ICES Journal of Marine Science 69: 1538-1548.

Chaput G., Legault, C. M., Reddin, D. G., Caron F. and Amiro, P. G. 2005. Provision of catch advice taking account of non-stationarity in productivity of Atlantic salmon (*Salmo salar* L.) in the Northwest Atlantic. ICES Journal of Marine Science 62: 131–143.

Chase, S. 2003. Closing the North American mixed-stock commercial fishery for wild Atlantic salmon pp. 84-92. In: D. Mills (Ed.) Salmon on the Edge. Blackwell Science, Oxford.

Clews, E., Durance, I., Vaughan, I. P. and Ormerod, S. J. 2010. Juvenile salmonid population in a temperate river system track synoptic trends in climate. Global Change Biology 16: 3271-3283.

Condron, A., DeConto, R. Bradley, R. S. and Juanes, F. 2005. Multidecadal North Atlantic climate variability and its effect on North American salmon abundance. Geophysical Research Letters 32: 1-4.

COSEWIC. 2010. COSEWIC assessment and status report on Atlantic salmon *Salmo salar*. Committee on the Status of Endangered Wildlife in Canada, Ottawa, 136 pp. www.sararegistry.gc.ca/status/statuse.cfm.

Crozier, W. W. and Kennedy, G. J. A. 1994. Marine exploitation of Atlantic salmon (*Salmo salar* L.) from the River Bush, Northern Ireland. Fisheries Research 19: 141-155.

Cunjak, R. A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Can. J. Fish. Aquat. Sci. 53: 267-282.

Cunjak, R. A., Caissie, D. El-Jabi, N. Hardie, P. Conlon, J. H. Pollock, T. L. Giberson, D. J. and Komadina-Douthwright , S. 1993. The Catamaran Brook (New Brunswick) habitat research project: biological, physical, and chemical conditions (1990-1992). Canadian Technical Report of Fisheries and Aquatic Sciences 1914. 81 pp.

Cunjak, R., Prowse, T. D. and Parrish, D. L.1998. Atlantic salmon (*Salmo salar*) in winter: “the season of parr discontent”. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 161-180.

Dempson, J. B., O’Connell, M. F. and Schwarz, C. J. 2004. Spatial and temporal trends in abundance of Atlantic salmon, *Salmo salar*, in Newfoundland with emphasis on impacts of the 1992 closure of the commercial fishery. Fisheries Management and Ecology 11: 387-402.

Dempson, J. B., Schwarz, C. J. Reddin, D. G. O’Connell, M. F. Mullins, C. C.and Bourgeois, C. E. 2001. Estimation of marine exploitation rates on Atlantic salmon (*Salmo salar* L.) stocks in Newfoundland, Canada. ICES Journal of Marine Science 58: 331-341.

DFO. 2012. Status of Atlantic salmon in Salmon Fishing Areas (SFAs) 19-21 and 23. Fisheries and Oceans Canada Science Advisory Secretariat Science Response 2012/014. 33 pp.

Dixon, H. J., Power, M. Dempson, J. B. Sheehan T. F. and Chaput, G. 2012. Characterizing the trophic position and shift in Atlantic salmon (*Salmo salar*) from freshwater to marine life-cycle phases using stable isotopes. ICES Journal of Marine Science 69: 1646-1655.

Downton, P. R., Reddin, D. G.and Johnson, R. W. 2001. Status of Atlantic salmon (*Salmo salar* L.) in Campbellton River, Notre Dame Bay (SFA4), Newfoundland in 2000. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2001/031. 73 p

Drinkwater, K. F. 2000. Changes in ocean climate and its general effect on fisheries: examples from the north-west Atlantic. In: D. Mills (Ed.) The Ocean Life of Atlantic Salmon: Environmental and Biological Factors Influencing Survival, p. 116-136. Fishing News Books, Blackwell Science, Oxford.

Dunbar, M. J. 1972. The nature and definition of the marine subarctic, with a note on the sea-life area of the Atlantic salmon. Transaction of the Royal Society of Canada, Series IV, Volume X: 249-257.

Dunbar, M. J. and Thomson, D. H. 1979. West Greenland salmon and climatic change. Meddekeser om Grønland 202(4): 5-19.

Dwyer, W. P. and Piper, R. G. 1987. Atlantic salmon growth efficiency as affected by temperature. Progressive Fish Culturist 49: 57-59.

Elliott, J. M. 1991. Tolerance and resistance to thermal stress in juvenile Atlantic salmon, *Salmo salar*. Freshwater Biology 25: 61-70.

Elliott, J. M. and Elliott, J. A. 2010. Temperature requirements of Atlantic salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. Journal of Fish Biology 77: 1793-1817.

Elliott, J. M. and Hurley, M. A. 1997. A functional model for maximum growth of Atlantic salmon parr, *Salmo salar*, from two populations in northwest England. Functional Ecology 11: 592-603.

Elliott, S. R., Coe, T. A., Helfield, J. M. and Naiman, R. J. 1998. Spatial variation in environmental characteristics of Atlantic salmon (*Salmo salar*) rivers. Canadian Journal of Fisheries and Aquatic Sciences 55: 267-280.

Fabry, V. J., Seibel, B. A. Feely, R. A. and Orr, J. C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science, 65: 414-432.

Fairchild, W. L., Swansburg, E. O., Arsenault, J. T. and Brown, S. B. 1999. Does an association between pesticide use and subsequent declines in catch of Atlantic salmon (*Salmo salar*) represent a case of endocrine disruption? Environmental Health Perspectives 107: 349-357.

Ferguson, A., Fleming, I. A. Hindar, K. Skaala, Ø. McGinnity, P. Cross, T. and Prodöhl, P. 2007. Farm escapes, pp. 357-398. In: The Atlantic Salmon: Genetics, Conservation and Management. E. Verspoor, L. Stradmeyer, and J. Nielsen [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Finstad, B., P. A. Bjørn, C. D. Todd, F. Whoriskey, P. G. Gargan, G. Forde and C. W. Revie. 2011a. The effect of sea lice on Atlantic salmon and other salmonid species, p. 2253-276. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Finstad, A. G., J. D. Armstrong and K. H. Nislow. 2011b. Freshwater habitat requirements of Atlantic salmon, pp. 67-87. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Finstad, A.G., Berg, O.K., Forseth, T., Ugedal, O. and Næsje, T.F. 2010. Adaptive winter survival strategies: defended energy levels in juvenile Atlantic salmon along a latitudinal gradient. Proceedings of the Royal Society B Biological Sciences, 277, 1113–1120.

Fletcher, G. L., Kao, M. H.and Dempson, J. B. 1988. Lethal freezing temperatures of Arctic char and other salmonids in the presence of ice. Aquaculture 71: 369-378.

Fleming, I. A. and Reynolds, J. D. 2004. Salmonid breeding systems. In Evolution illuminated: salmon and their relatives, pp. 264-294. Henry, A. P., and S. C. Stearns [eds.] Oxford University Press, Oxford, New York.

Forseth, T., Letcher, B. H. and Johansen, M. 2011. The behavioural flexibility of salmon growth, pp. 145-169. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Friedland, K. D. and Haas, R. E. 1996. Marine post-smolt growth and age at maturity of Atlantic salmon. Journal of Fish Biology 48: 1-15.

Friedland, K. D., Hansen, L. P. and Dunkley, D. A. 1998. Marine temperatures experienced by postsmolts and the survival of Atlantic salmon, *Salmo salar* L., in the North Sea area. Fisheries Oceanography 7: 22-34.

Friedland, K. D., Hansen, L. P. Dunkley, D. A. and MacLean, J. C. 2000. Linkage between ocean climate, post-smolt growth, and survival of Atlantic salmon *Salmo salar* L., in the North Sea area. ICES Journal of Marine Science 57: 419-429.

Friedland, K. D., MacLean, J. C. Hansen, L. P. Peyronnet, A. J. Karlsson, L. Reddin, D. G. Maoiléidigh, N. Ó and McCarthy, J. L. 2009. The recruitment of Atlantic salmon in Europe. ICES Journal of Marine Science 66: 289-304.

Friedland, K. D., Reddin, D. G. and Kocik, J. F. 1993. Marine survival of North American and European Atlantic salmon: effects of growth and environment. ICES Journal of Marine Science 50: 481-492.

Friedland, K. D., Reddin, D. G. McMenemy, J. R. and Drinkwater, K. F. 2003. Multidecadal trends in North American Atlantic salmon (*Salmo salar*) stocks and climate relevant to juvenile survival. Canadian Journal of Fisheries and Aquatic Sciences 60: 563-583.

Friedland, K. D. and Todd, C. D. 2012. Changes in Northwest Atlantic Arctic and Subarctic conditions and the growth response of Atlantic salmon. Polar Biology 35: 593-609.

Gausen, D. and Moen, V. 1991. Large-scale escapes of farmed Atlantic salmon (*Salmo salar*) into Norwegian rivers threaten natural populations. Canadian Journal of Fisheries and Aquatic Sciences 48(3):426–428.

Gibson, A. J. F., Bowlby, H. D. Hardie, D. C. and O'Reilly, P. T. 2011. Populations on the brink: low abundance of Southern Upland Atlantic salmon in Nova Scotia, Canada. North American Journal of Fisheries Management 31: 733-741.

Gibson, R. J. 1978. The behaviour of juvenile Atlantic salmon (*Salmo salar*) and brook trout (Salvelinus fontinalis) with regard to temperature and to water velocity. Transactions of the American Fisheries Society 107, 703-712.

Gibson, R. J. 1988. Mechanisms regulating species composition, population structure, and production of stream salmonids; a review. Poliskie Archiwum Hydrobiologii 35: 469- 495.

Gibson, R. J. 1993. The Atlantic salmon in fresh water: spawning rearing and production. Reviews in Fish Biology and Fisheries 3: 39-73.

Gibson, R. J. 2002. The effects of fluvial processes and habitat heterogeneity on distribution, growth and densities of juvenile Atlantic salmon (*Salmo salar* L.), with consequence on abundance of the adult fish. Ecology of Freshwater Fish 11: 207-222.

Gibson, R. J., Stansbury, D. E. Whalen, R. R. and Hillier, K. G. 1993. Relative habitat use, and inter-specific and intra-specific competition of brook trout (Salvelinus fontinalis) and juvenile Atlantic salmon (*Salmo salar*) in some Newfoundland rivers. In Production of juvenile Atlantic salmon, *Salmo salar*, in natural waters, pp. 53-69. Canadian Special Publication of Fisheries and Aquatic Sciences 118. 262 pp.

Graham, C. T. and Harrod, C. 2009. Implications of climate change for the fishes of the British Isles. Journal of Fish Biology 74: 1143-1205.

Grant, J.W.A., Steingrímsson, S.Ó., Keeley, E.R. and Cunjak, R.A. 1998. Implications of territory size for the measurement and prediction of salmonid abundance in streams. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 181-190.

Hamor, T. and Garside, E. T. 1976. Developmental rates of embryos of Atlantic salmon, *Salmo salar* L., in response to various levels of temperature, dissolved oxygen, and water exchange. Canadian Journal of Zoology 54: 1912-1917.

Hansen, L. P. 1988. Status of exploitation of Atlantic salmon in Norway. In: D. Mills and D. Piggins (Eds.) Atlantic Salmon: Planning for the Future, p. 143-161. Croom Helm, London.

Hansen, L. P. 1990 Exploitation of Atlantic salmon (*Salmo salar* L.) from the River Drammenselv, SE Norway. Fisheries Research 10: 125-135.

Hansen, L. P. and Jonsson, B. 1991a. Evidence of a genetic component in the seasonal return pattern of Atlantic salmon, *Salmo salar* L. Journal of Fish Biology 38: 251-258.

Hansen, L. P. and Jonsson, B.1991b. The effect of timing of Atlantic salmon smolt and post-smolt release on the distribution of adult return. Aquaculture 98: 61-67.

Hansen, L. P. and Quinn, T. P. 1998. The marine phase of the Atlantic salmon (*Salmo salar*) life cycle, with comparisons to Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 104-118.

Harris, P. D., Bachmann, L. and Blake, T. A. 2011. The parasites and pathogens of the Atlantic salmon: lessons from *Gyrodactylus salaris*, pp. 221-252. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Hedger, R. D., Næsje, T. F. Fiske, P., Ugedal, O., Finstad, A. G. and Thorstad, E. B. 2013. Ice-dependent winter survival of juvenile Atlantic salmon. Ecology and Evolution 3: 523-535.

Heggenes, J., Baglinière, J. L. and Cunjak, R.A. 1999. Spatial niche variability for young Atlantic salmon (*Salmo salar*) and brown trout (*S. trutta*) in heterogeneous streams. Ecology of Freshwater Fish 8: 1-21.

Horreo, J. L., Machado-Schiaffino, G. Griffiths, A. M. Bright, D. Stevens, J. R. and Garcia-Vazquez, E. 2011. Atlantic salmon at risk: Apparent rapid declines in effective population size in southern European populations. Tranactions of the American Fisheries Society 140: 605-610.

Hutchings, J. A. 1986. Lakeward migrations by juvenile Atlantic salmon, *Salmo salar*. Canadian Journal of Fisheries and Aquatic Sciences 43: 732-741.

Hutchings, J. A. and Jones, M. E. B.1998. Life history variation and growth rate thresholds for maturity in Atlantic salmon, *Salmo salar*. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 22-47.

Hutchinson, P. (ed) 1997. Interactions between salmon culture and wild stocks of Atlantic salmon: the scientific and management issues. ICES Journal of Marine Science 54: 963-1227.

Hutchinson, P., Welch, D., D. Boehlert, G. and Whelan, K. 2002. A synthesis of the joint meeting: Causes of marine mortality of salmon in the North Pacific and North Atlantic oceans and in the Baltic Sea. North Pacific Anadromous Fish Commission Technical Report 4: 93-96.

ICES. 2012. Report of the Working Group on North Atlantic Salmon (WGNAS), 26-March- 4 April 2012. Copenhagen, Denmark. ICES CM 2012/ACOM:09. 322 pp.

Javaid, M. Y. and Anderson, J. M. 1967. Thermal acclimation and temperature selection in Atlantic salmon, *Salmo salar*, and rainbow trout, *S. gairdneri*. Journal of the Fisheries Research Board of Canada 24: 1507-1513.

Jensen, A. J., Johnsen, B. O.and Saksgard, L. 1989. Temperature requirements in Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*), and Arctic Char (*Salvelinus alpinus*) from hatching to initial feeding compared with geographic distribution. Canadian Journal of Fisheries and Aquatic Sciences 46: 786-789.

Jonsson, N. 1991. Influence of water flow, water temperature and light on fish migration in rivers. Nordic Journal of Freshwater Research 66:20-35.

Jonsson, B. and Jonsson, N. 2006. Cultured Atlantic salmon in nature: a review of their ecology and interaction with wild fish. ICES Journal of Marine Science 63: 1162-1181.

Jonsson, B. and Jonsson, N. 2009. A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*, with particular reference to water temperature and flow. Journal of Fish Biology 75: 2381-2447.

Jonsson, N. and Jonsson, B. 2004a. Factors affecting marine production of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Science 61: 2369-2383.

Jonsson, B. and Jonsson, N. 2004b. Size and age of maturity of Atlantic salmon correlate with the North Atlantic Oscillation Index (NAOI). Journal of Fish Biology 64: 241-247.

Jonsson, N., Hansen, L. P. and Jonsson, B. 1991. Variation in age, size and repeat spawning of adult Atlantic salmon in relation to river discharge. Journal of Animal Ecology 60: 937-947.

Jonsson, N., Jonsson, B. and Hansen, L. P. 2003. The marine survival and growth of wild and hatchery-reared Atlantic salmon. Journal of Applied Ecology 40: 900-911.

Jonsson, N., B. Jonsson and L. P. Hansen. 2005. Does climate during embryonic development influence parr growth and age of seaward migration in Atlantic salmon (*Salmo salar*) smolts? Canadian Journal of Fisheries and Aquatic Sciences 62: 2502-2508.

Jonsson, B., Jonsson, N.and Hansen, L. P. 2007. Factors affecting river entry of adult Atlantic salmon in a small river. Journal of Fish Biology 71: 943-956.

Juanes, F., Gephard, S. and Beland, K. F. 2004. Long-term changes in migration timing of adult Atlantic salmon (*Salmo salar*) at the southern edge of the species distribution. Canadian Journal of Fisheries and Aquatic Sciences 61: 2392-2400.

Karvonen, A., Rintamäki, P. Jokela, J. and Valtonen, E. T. 2010. Increasing water temperature and disease risks in aquatic systems: Climate change increases the risk of some, but not all, diseases. International Journal of Parasitology 40: 1483-1488.

Keenleyside, M. H. A. 1962. Skin-diving observations of Atlantic salmon and brook trout in the Miramichi River, New Brunswick. Journal of the Fisheries Research Board of Canada 19: 625-634.

Kennedy, R. J. and Crozier, W. W. 2010. Evidence of changing migratory patterns of wild Atlantic salmon *Salmo salar* smolts in the River Bush, Northern Ireland, and possible associations with climate change. Journal of Fish Biology 76: 1786-1805.

King, H.R., Pankhurst, N.W., Watts, M. and Pankhurst P.M. 2003. Effect of elevated summer temperatures on gonadal steroid production, vitellogenesis and egg quality in female Atlantic salmon. Journal of Fish Biology 63: 153-167.

Klemetsen, A., Amundsen, P.-A. Dempson, J. B. Jonsson, B. Jonsson, N. O'Connell, M. F. and Mortensen, E. 2003. Atlantic salmon *Salmo salar* L., brown trout *Salmo trutta* L. and Arctic charr *Salvelinus alpinus* (L.): a review of aspects of their life histories. Ecology of Freshwater Fish 12: 1-59.

MacCrimmon, H. R. and Gots, B. L. 1979. World distribution of Atlantic salmon, *Salmo salar*. Journal of the Fisheries Research Board of Canada 36: 422-457.

Marcogliese, D. J. 2001. Implications of climate change for parasitism of animals in the aquatic environment. Canadian Journal of Zoology 79: 1331-1352.

Marcogliese, D. J. 2008. The impact of climate change on the parasites and infectious diseases of aquatic animals. Revue scientifique et technique (International Office of Epizootics) 27: 467-484.

Marschall, E. A., Quinn, T. P. Roff, D. A. Hutchings, J. A. Metcalfe, N. B. Bakke, T. A. Saunders R. L. and Poff, N. L.1998. A framework for understanding Atlantic salmon (*Salmo salar*) life history. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 48-58.

Mather, M.E., Parrish, D.L., Campbell, C.A., McMenemy, J.R., Smith, J.M. 2008. Summer temperature variation and implications for juvenile Atlantic salmon. Hydrobiologia 603: 183-196.

Mathes, M. T., Hinch, S. G. Cooke, S. J. Crossin, G. T. Patterson, D. A. Lotto, A. G. and Farrell. A. P. 2010. Effect of water temperature, timing, physiological condition, and lake thermal refugia on migrating adult Weaver Creek sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences 67: 70-84.

McCarthy, I. D. and Houlihan, D. F. 1997. The effect of temperature on protein metabolism in fish: the possible consequences for wild Atlantic salmon (*Salmo salar* L.) stocks in Europe as a result of global warming, pp. 51-77. In: Global warming: implications for freshwater and marine fish. C. M. Wood and D. G. McDonald [eds.], Cambridge University Press, Cambridge U.K.

McCormick, S. D., Hansen, L. P. Quinn, T. P.and Saunders, R. L. 1998. Movement, migration, and smolting of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 77-92.

Meerburg, D.J., ed. 1986. Salmonid age at maturity. Canadian Special Publication of Fisheries and Aquatic Sciences 89, 118 p.p.

Metcalfe, N. B. 1994. The role of behaviour in determining salmon growth and development. Aquaculture and Fisheries Management 25: 67-76.

Metcalfe, N. B. and Thorpe, J. E. 1990. Determinants of geographic variation in the age of seaward-migrating salmon, *Salmo salar*. Journal of Animal Ecology 59: 135-145.

Middlemas, S. J., Armstrong, J. D. and Thompson, P. M. 2003. The significance of marine mammal predation on salmon and sea trout. In: D. Mills (ed.) Salmon at the edge, p. 43-60. Fishing News Books, Blackwell Scientific Publications, Oxford.

Mills, D. H. 1993. Control of marine exploitation. In: D. Mills (ed.) Salmon in the Sea and New Enhancement Strategies, p. 233-248. Fishing News Books, Blackwell Scientific Publications, Oxford.

Mills, D. (ed) 2000. The Ocean Life of Atlantic Salmon: Environmental and Biological Factors Influencing Survival. Oxford: Fishing News Books, Blackwell Science, 228 pp.

Minns, C. K., R. G. Randall, E. M. P. Chadwick, J. E. Moore and R. Green. 1995. Potential impact of climate change on the habitat and population dynamics of juvenile Atlantic salmon (*Salmo salar*) in eastern Canada. Canadian Special Publication of Fisheries and Aquatic Sciences 121: 699-708.

Montevecchi, W. A., D. K. Cairns and R. A. Myers. 2002. Predation on marine-phase Atlantic salmon (*Salmo salar*) by gannets (Morus bassanus) in the northwest Atlantic. Canadian Journal of Fisheries and Aquatic Sciences 59: 602-612.

Nielsen, J. L., G. T. Ruggerone and C. E. Zimmerman. 2013. Adaptive strategies and life history characteristics in a warming climate: salmon in the Arctic? Environmental Biology of Fishes 96: 1187-1226.

O'Connell, M. F. and E.G., M. Ash. 1989. Atlantic salmon (*Salmo salar*) smolt production in a Newfoundland river system characterized by lacustrine habitat. Internationale Revue der Gesamten Hydrobiologie 74: 73-82.

O'Connell, M. F. and E.G., M. Ash. 1993. Smolt size in relation to age at first maturity of Atlantic salmon (*Salmo salar*): the role of lacustrine habitat. Journal of Fish Biology 42: 551-569.

O'Connell, M. F. and J. B. Dempson. 1996. Spatial and temporal distributions of salmonids in two ponds in Newfoundland, Canada. Journal of Fish Biology 48: 738-757.

O'Connell, M. F., J. B. Dempson and G. Chaput. 2006. Aspects of the life-history, biology, and population dynamics of Atlantic salmon (*Salmo salar* L.) in Eastern Canada. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat Research Document 2006/014, 47 p.

O'Connell, M.F., Reddin, D.G., Amiro, P.G., Caron, F., Marshall, T.L., Chaput, G., Mullins, C.C., Lock, A., O'Neil S.F. and Cairns D.K. 1997. Estimates of the conservation spawner requirements for Atlantic salmon (*Salmo salar* L.) for Canada. Canadian Stock Assessment Secretariat Research Document 97/100, 58 p.

Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely et al. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437: 681-686.

Otero, J., L' Abée-Lund, J. H., Castro-Santos, T., Leonardsson, K., Storvik, G. O., Jonsson, B., Dempson, B., Russell, I. C., Jensen, A. J., Baglinière, Dionne, M. et al. 2014. Basin-scale phenology and effects of climate variability on global timing of initial seaward migration of Atlantic salmon (*Salmo salar*). Global Change Biology 20: 61-75.

Parrish, D. L., Behnke, R. J. Gephard, S. R. McCormick S. D. and Reeves, G. H. 1998. Why aren't there more Atlantic salmon (*Salmo salar*)? Can. J. Fish. Aquat. Sci. 55(Suppl. 1): 281-287.

Pepper, V. A., N. P. Oliver and R. Blunden. 1985. Juvenile anadromous Atlantic salmon of three lakes of Newfoundland. Internationale Revue der Gesamten Hydrobiologie 70:733-753

Peterson, R. H. and D. J. Martin-Robichaud. 1989. First feeding of Atlantic salmon fry as influenced by temperature regime. Aquaculture 78: 35-53.

Peyronnet, A., K. D. Friedland and N. Ó Maoiléidigh. 2008. Different ocean and climate factors control the marine survival of wild and hatchery Atlantic salmon *Salmo salar* in the north-east Atlantic Ocean. Journal of Fish Biology 73: 945-962.

Peyronnet, A., K. D. Friedland, N. Ó Maoiléidigh, M. Manning and W. R. Poole. 2007. Links between patters of marine growth and survival of Atlantic salmon *Salmo salar*, L. Journal of Fish Biology 71: 684-700.

Porter, T. R., M. C. Healey, M. F. O'Connell, E. T. Baum, A. T. Bielak and Y. Côté. 1986. Implications of varying sea age at maturity of Atlantic salmon (*Salmo salar*) on yield to the fisheries. In Salmonid age at maturity, pp. 110-117. D. J. Meerburg [ed.] Canadian Special Publication of Fisheries and Aquatic Sciences 89. 118 pp.

Potter, E. C. E. and W. W. Crozier. 2000. A perspective on the marine survival of Atlantic salmon. In: D. Mills (Ed.) The Ocean Life of Atlantic Salmon: Environmental and Biological Factors Influencing Survival, p. 19-36. Fishing News Books, Blackwell Science, Oxford.

Potter, E. C. E., W. W. Crozier, P-j. Schön, M. D. Nicholson, E. Prévost, E. Erkinaro, G. Gudbergsson, L. Karlsson, L. P. Hansen, J. C. MacLean, N. Ó Maoiléidigh and S. Prusov. 2004. Estimating and forecasting pre-fishery abundance of Atlantic salmon (*Salmo salar* L.) in the Northeast Atlantic for the management of mixed-stock fisheries. ICES Journal of Marine Science 61: 1359-1369.

Power, G. 1958. The evolution of the freshwater races of the Atlantic salmon (*Salmo salar* L.) in eastern North America. Arctic 11: 86-92.

Power, G. 1969. The salmon of Ungava Bay. Arctic Institute of North America. Technical Paper No. 22. 72 pp.

Power, G. 1981. Stock characteristics and catches of Atlantic salmon (*Salmo salar*) in Quebec, and Newfoundland and Labrador in relation to environmental variables. Canadian Journal of Fisheries and Aquatic Sciences 38: 1601-1611.

Power, G. 1986. Physical influences on age at maturity of Atlantic salmon (*Salmo salar*): a synthesis of ideas and questions. Canadian Special Publication of Fisheries and Aquatic Sciences 89: 97-101.

Power, G. 1990. Salmonid communities in Quebec and Labrador: temperature relations and climate change. Polskie Archiwum Hydrobiologii 37(1-2): 13-28.

Pulkkinen, K., L.-R. Suomalainen, A. F. Read, D. Ebert, P. Rintamäki and E. T. Valtonen. 2010. Intensive fish farming and the evolution of pathogen virulence: the case of columnaris disease in Finland. Proceedings of the Royal Society B 277: 593-600.

Randall, R. G. and U. Paim. 1982. Growth, biomass and production of juvenile Atlantic salmon (*Salmo salar*) in two Miramichi River, New Brunswick, tributary streams. Canadian Journal of Zoology 60: 1647-1659.

Randall, R. G., M. C. Healey, and J. B. Dempson. 1987. Variability in length of freshwater residence by species of the subfamily Salmoninae. American Fisheries Society Symposium 1:27 41.

Randall, R.G., J. E. Thorpe, R. J. Gibson and D. G. Reddin. 1986. Biological factors affecting age at maturity in Atlantic salmon (*Salmo salar*). In: Meerburg, D.J., ed. Salmonid age at maturity. Canadian Special Publication of Fisheries and Aquatic Sciences 89, pp.90-96.

Reist, J. D., F. J. Wrona, T. D. Prowse, M. Power, J. B. Dempson, J. R. King and R. J. Beamish. 2006. An overview of effects of climate change on selected Arctic freshwater and anadromous fishes. Ambio 35: 381-387.

Riddell, B.E. 1986. Assessment of selective fishing on the age at maturity in Atlantic salmon (*Salmo salar*): a genetic perspective. In: Meerburg, D.J., ed. Salmonid age at maturity. Canadian Special Publication of Fisheries and Aquatic Sciences 89, pp.102-109.

Rikardsen, A. H. and J. B. Dempson. 2011. Dietary life-support: the food and feeding of Atlantic salmon at sea, pp. 115-143. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Ritter, J. A. 1993. Changes in Atlantic salmon (*Salmo salar*) harvests and stock status in the North Atlantic. In: D. Mills (Ed.) Salmon in the sea and new enhancement strategies, pp. 3-25. Fishing News Books, Blackwell Science, Oxford.

Robertson, M. J., J. B. Dempson, D. G. Reddin, G. I Veinott, N. M. Cochrane, C. E. Bourgeois and D. Caines. 2010. Status of Atlantic salmon (*Salmo salar* L.) stocks of insular Newfoundland (SFAs 3-14A), 2009. Fisheries and Oceans Canada, Canadian Science Advisory Secretariat, Research Document 2010/139, 50 pp.

Robitaille, J. A., Y. Côté, G. Shooner and G. Hayeur. 1986. Growth and maturation patterns of Atlantic salmon, *Salmo salar*, in Koksoak River, Ungava, Quebec, pp. 62-69. In Salmonid age at maturity, D. J. Meerburg [ed.] Canadian Special Publication of Fisheries and Aquatic Sciences 89. 118 p.

Rosseland, B. O. and F. Kroglund. 2011. Lessons from acidification and pesticides, pp. 387-407. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Russell, I. C., M. W. Aprahamian, J. Barry, I. C. Davidson, P. Fiske et al. 2012. The influence of the freshwater environment and the biological characteristics of Atlantic salmon smolts on their subsequent marine survival. ICES Journal of Marine Science 69: 1563-1573.

Salminen, M., Kuikka, S. and Erkamo, E. 1995. Annual variability in survival of sea-ranched Baltic salmon, *Salmo salar* L.: significance of smolt size and marine conditions. Fisheries Management and Ecology 2: 171-184.

Saunders, R. L. and C. B. Schom. 1985. Importance of the variation in life history parameters of Atlantic salmon (*Salmo salar*). Canadian Journal of Fisheries and Aquatic Sciences 42: 615-618.

Schaffer, W. M. 1974. Selection for optimal life histories: the effects of age structure. Ecology 55: 291-303.

Solomon, D. J. and H. T. Sambrook. 2004. Effects of hot dry summers on the loss of Atlantic salmon, *Salmo salar*, from estuaries in South West England. Fisheries Management and Ecology 11: 353-363.

Stabell, O. B. 1982. Homing of Atlantic salmon in relation to olfaction and genetics. In Proceedings of the salmon and trout migratory behavior symposium, pp. 71-78.

Stabell, O. B. 1984. Homing and olfaction in salmonids: a critical review with special reference to the Atlantic salmon. Biological Reviews 59: 333-388.

Strothotte, E., G. J. Chaput and H. Rosenthalt. 2005. Seasonal growth of wild Atlantic salmon (*Salmo salar* L.) juveniles and implications on age at smoltification. Journal of Fish Biology 67: 1585-1602.

Swansburg, E., G. Chaput, D. Moore, D. Caissie and N. El-Jabi. 2002. Size variability of juvenile Atlantic salmon: links to environmental conditions. Journal of Fish Biology 61: 661-683.

Swansburg, E., N. El-Jabi and D. Caissie. 2004. Climate change in New Brunswick (Canada): statistical downscaling of local temperature, precipitation, and river discharge. Canadian Technical Report of Fisheries and Aquatic Sciences 2544. 42 pp.

Taylor, E. B. 1991. A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon. Aquaculture 98: 185-207.

Thistle, M. E. and D. Caissie. 2013. Trends in air temperature, total precipitation, and streamflow characteristics in eastern Canada. Canadian Technical Report of Fisheries and Aquatic Sciences 3018. 97 pp.

Thorpe, J. E., M. Mangel, N. B. Metcalfe and F. A. Huntingford. 1998. Modelling the proximate basis of salmonid life-history variation, with application to Atlantic salmon, *Salmo salar* L. Evolutionary Ecology 12: 581-599.

Thorstad, E. B., F. Økland, K. Aarestrup and T. G. Heggberget. 2008. Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts. Reviews in Fish Biology and Fisheries 18: 345-371.

Thorstad, E. B., F. Whoriskey, A. H. Rikardsen and K. Aarestrup. 2011. Aquatic nomads: migrations of the Atlantic salmon, pp. 1-32. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Todd, C. D., K. D. Friedland, J. C. MacLean, N. Hazon and A. J. Jensen. 2011. Getting into hot water? Atlantic salmon responses to climate change in freshwater and marine environments, pp. 409-443. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Todd, C. D., K. D. Friedland, J. C. MacLean, B. D. Whyte, I. C. Russell, M. E. Lonergan and M. B. Morrissey. 2012. Phenological and phenotypic changes in Atlantic salmon populations in response to a changing climate. ICES Journal of Marine Science 69: 1686-1698.

Todd, C. D., S. L. Hughes, T. Marshall, J. C. MacLean, M. E. Lonergan and E. M. Biow. 2008. Detrimental effects of recent ocean surface warming on growth condition of Atlantic salmon. Global Change Biology 14: 1-13.

Ward, D. M. and N. A. Hvidsten. 2011. Predation: compensation and context dependence, pp. 199-220. In: Atlantic Salmon Ecology, Ø. Aas, S. Einum, A. Klemetsen, and J. Skurdal [Eds]. Blackwell Publishing Ltd. Oxford, UK.

Zitko, V. 1995. Fifty years of research on the Miramichi River. In: E. M. P. Chadwick (ed) Water, science, and the public: the Miramichi ecosystem, p. 29-41. Canadian Special Publication of Fisheries and Aquatic Sciences 123.

Chapter 6 Climate change and marine aquaculture in Atlantic Canada and Quebec

N. Feindel, L. Cooper*, E. Trippel, and T. Blair

Maritimes Region, St. Andrews Biological Station, 531 Brandy Cove Road,
St. Andrews, New Brunswick E5B 2L9

*Correspondence: Lara.Cooper@dfo-mpo.gc.ca

Suggested Citation:
Feindel, N., L. Cooper, E. Trippel and T. Blair. 2013. Climate change and marine aquaculture in Atlantic Canada and Quebec. Ch. 6 (p. 195–240) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

6.1 SUMMARY

Aquaculture is an established and growing industry in Canada and globally. Identifying the implications of climate change to this sector is essential for the long-term viability of aquaculture in Canada. This contribution to the federal Aquatic Climate Change Adaptation Services Program (ACCASP) assesses the impacts, vulnerabilities and opportunities of climate change on marine-based aquaculture in Eastern Canada's Atlantic region. Our objectives were to (1) examine the major species being farmed in Atlantic Canada, their economic value and the observed and expected impacts climate change could have on individual species, (2) identify from published literature and other sources the optimal growing conditions and lethal environmental thresholds (for temperature, oxygen, pH, and salinity) of the major species being farmed in Atlantic Canada, and (3) make recommendations for future research to address gaps in knowledge that are needed to be filled to improve our ability to predict the effects of climate change to marine-based aquaculture in the Atlantic Region.

6.2 INTRODUCTION

Aquaculture supplied the world with approximately 77 million tonnes of fish in 2010, representing about 50% of the seafood consumed globally (FAO, 2009). This volume represents a rapid growth in aquaculture production, which totalled about 25% of global seafood supply just a decade ago. In Canada, aquaculture production provides approximately 6,000 direct, full time equivalent jobs for Canadians and some 9,700 more positions in the supplies, services and support sectors. With a gross value of more than $2.1 billion, the Canadian aquaculture industry contributes significantly to the broader Canadian economy, providing more than $1 billion toward Canada's direct, indirect and induced gross domestic product. Therefore, it is important that we monitor and predict the impacts that climate change will have on aquaculture, and focus future research on mitigating negative impacts and taking advantage of positive ones.

All species have a range of environmental parameters in which they can live—defined as the fundamental niche. Climate change will result in temporal and spatial shifts in the fundamental niche of species. Cultured species differ from wild species in that they cannot avoid areas that are outside of their fundamental niche, or even areas that are outside of their optimum for growth and survival. There are several potential impacts from climate change on aquaculture production in the marine environment. These can be classified as direct or indirect effects. These are summarised well by Handisyde et al. 2006.

Table 6–1 Potential impacts of climate change on cultured marine species in the Atlantic basin (modified from Handisyde et al. 2006 and Cochrane et al. 2009).

Drivers of Change	Impacts on Culture Systems	Operational Impacts
Sea surface temperature changes	• Longer growing seasons • Changes in locations and ranges of suitable species • Reduced winter natural mortality • Enhanced growth and food conversion rates • Decreased dissolved O_2 • Increased disease and parasites • Increase in harmful algal blooms • Competition, parasitism and predation from altered local ecosystems, competitors, and exotic species	• Changes in infrastructure and operation costs • Increased fouling, pests, nuisance species and predators • Expanded geographic ranges for species • Changes in production levels
Changes in other oceanographic variables (wind velocity, currents, and wave action)	• Decreased flushing rates and food availability to shellfish • Changes in abundance of species used for food and fishmeal	• Accumulation of wastes under nets • Increased operating costs
Sea level rise	• Loss of areas for aquaculture • Loss of areas providing physical protection	• Infrastructure damage • Change in aquaculture zoning

		• Increased insurance costs
Increased storm activity	• Larger waves • Higher storm surges • Salinity changes • Structural damage	• Loss of stock • Facility and net pen damage • Higher costs for designing new facilities and net pens • Increased insurance costs

The key environmental variables that have the potential to impact the culture of organisms in the marine environment are temperature, salinity, oxygen and pH. The impact from changes in these variables will vary by species and geographic location. These differences need to be considered by resource managers and policymakers when considering climate change impacts on aquaculture.

In addition to the direct effects from changes in key environmental variables, indirect effects as a result of an increase in extreme weather events and harsh environmental conditions, increased scope for aquatic invasive species, increases in harmful algal blooms, and increased threats from disease and parasites also need to be considered.

6.3 ECONOMIC VALUE AND PRODUCTION OF MARICULTURE IN ATLANTIC CANADA AND QUEBEC

The following table indicates which species are farmed in the Atlantic Provinces (by tonnage) and their economic value.

Table 6–2 Aquaculture, production (tonnes) and value (thousands of dollars), by Atlantic Provinces and Quebec—2010 (modified from Statistics Canada-Catalogue no. 23-222-X).

	Newfoundland and Labrador	Prince Edward Island	Nova Scotia	New Brunswick	Quebec	Total[1]
Production (tons)						
Salmon	--	--	4,960	25,625	0	30,585
Other finfish[2]	--	--	91	0	0	91
Total marine finfish	**12,899**	**--**	**5,051**	**25,625**	**0**	**43,575**
Clams	0	0	438	0	0	438
Oysters	0	2,377	205	881	0	3,463
Mussels	2,461	18,845	2,121	95	563	24,085
Scallops	0	0	2	0	0	2
Other shellfish	0	0	172	0	5	177
Total shellfish	**2,461**	**21,222**	**2,938**	**976**	**568**	**28,165**

	Newfoundland and Labrador	Prince Edward Island	Nova Scotia	New Brunswick	Quebec	Total[1]
Value ('000's of dollars)						
Salmon	--	--	29,314	162,000	0	191,314
Other finfish[2]	--	--	2,727	0	0	2,727
Total marine finfish	**110,301**	**--**	**32,044**	**162,000**	**0**	**304,345**
Clams	--	0	190	0	0	190
Oysters	--	5,288	720	5,500	0	11,508
Mussels	6,009	24,966	2,548	100	782	34,405
Scallops	--	0	15	0	0	15
Other shellfish		0	4,896	0	47	4,943
Total shellfish	**6,009**	**30,254**	**8,369**	**5,600**	**828**	**51,060**

1. Provinces with data not available are not included in the totals.
2. Other finfish data is only available at the Canada level and includes confidential data from the provinces.

6.4 PROFILES OF KEY CULTURED SPECIES IN ATLANTIC CANADA AND QUEBEC

For the figures referenced in the text, and summary tables of environmental thresholds for key cultured species in Atlantic Canada and Quebec, please refer to this chapter's Appendices.

6.4.1 Atlantic Salmon (*Salmo salar*)

Atlantic salmon are cultured in New Brunswick at 90+ marine finfish sites in six bay management areas (Appendix 6.1, Fig. 6–1). Salmon culture is also practiced in Newfoundland (Appendix 6.1, Fig. 6–2) and in Nova Scotia from Annapolis County to Inverness County (Appendix 6.1, Fig. 6–3).

Temperature and oxygen are among the most critical characteristics to consider when assessing locations for commercial salmon production (Appendix 6.2, Table 6–3). The optimal temperature range based on growth in sea-cages in Nova Scotia and New Brunswick, for smolt to market sized salmon is 8-12 °C (Saunders, 1995). This is notably lower than for Norwegian strains where growth rates increase as temperature increases up to 14 °C in sea cages (Austreng et al, 1987). A number of Norwegian studies have shown that temperature optima for maximum growth increases with body mass. For post-smolts, optima are 12.8± 0.2 °C for 70-150 g fish and 14.0± 0.4 °C for 170-300 g fish with fish at 6 °C having significantly lower growth rates (Handeland et al, 2003,2008). There was only a slight difference in growth between 14 °C and 18 °C with a significant drop in appetite above 18 °C, comparable to the 6 °C temperature level (Handeland et al, 2003, 2008). Temperatures above 16 °C are considered unfavourable for salmon as it increases chances of disease outbreaks or algae and phytoplankton blooms which can severely depress oxygen levels in sea cages (Saunders, 1995). The upper critical range for survival is 22-28 °C, where 50% of the fish can tolerate these temperatures for approximately 7 days, and a upper lethal limit of 30-33 °C, where fish can only tolerate these temperatures for 10 minutes (Elliott and Elliott, 2010). It has been shown that the lower lethal limit for salmon is -0.7 °C (Saunders et al. 1975; Saunders 1987), which has resulted in high mortality in sea cages in the northwest Atlantic (Elliott and Elliott 2010). Salmon feed minimally at temperatures ≤ 6 °C which is unfavourable for growth and cease feeding around 1 °C (Saunders et al. 1975; Handeland et al, 2003, 2008). As climate change begins to increase ocean temperatures, it may result in seasons being shortened or lengthened. Salmon may only be exposed to critical winter temperatures for a shorter time period resulting in a longer optimal growing period. However, if temperature increases at a rapid rate during spring and summer (optimal growing time), salmon will be exposed to prolonged temperature increases and in some areas be exposed to elevated temperature for the entire growing season. This may affect the welfare of the salmon, increase stress and could result in poor production and in some cases mortality for certain areas.

Increases in temperature result in an exponential increase in oxygen consumption in salmon (Forsberg, 1994), which can lead to low oxygen levels and hypoxic events in sea-cages. Areas that encounter hypoxic events, extended periods of time where oxygen levels are ≤ 6 mg/L (Burt et al, 2011; Chang et al, 2009; Mansour et al, 2008), are considered stressful. At a salinity of 34 ppt, 6 mg/L is equivalent to approximately 55%, 61%, 66%, 72%, 78% saturation at 2, 6, 10, 14 and 18 °C respectively (Burt et al. 2011). Areas that have a constant oxygen supply of ≥ 8 mg/L are considered ideal for optimum growth (Forsberg and Bergheim, 1996; Thorarensen and Farrell 2011). The critical threshold for salmon is when oxygen levels reach 2.0-2.5 mg/L (Kazakov and Khalyapina 1981). Fish become agitated and try to surface for air and if levels drop further to concentrations ranging between 1.5-1.7 mg/L the fish asphyxiate and die (Kazakov and Khalyapina 1981). There are a number of factors that may affect oxygen levels on sites, so seasonal and physical profiles of the water column, with and without fish, need to be considered for selection of future sites to achieve optimal production. A study in Newfoundland monitored three different salmon sites in Fortune Bay to determine the variability in physical characteristics (temperature and oxygen) of the sites over time (Mansour et al, 2008). Profiles of hypoxic events were shown to be prominent in summer and early fall with one site having year round hypoxia. This led to the site being reoriented to improve oxygen levels in hopes of improving culture conditions. The presence of fish on a site can also reduce oxygen levels and this is one factor that has to be considered in models for site selection (Wildish et al, 1993; Chang et al, 2009). A study of two sites in Southwest New Brunswick showed that fish were having an impact on dissolved oxygen within a cage site (Chang et al, 2009). Through the use of models it can be determined how long it would take for a certain biomass of fish to reduce the oxygen level to the threshold (6 mg/L) in the absence of ocean currents. In New Brunswick, through the use of "The Page Oxygen Model" at one site, a biomass of 60,600 kg could reduce oxygen down to 6 mg/L in 1.4h if feeding and 2.9h if not feeding. It was also shown at a second site that a biomass of 115,000 kg could reduce oxygen to 6 mg/L in 0.9h if feeding and 1.9h if not feeding (Chang et al, 2009). In Newfoundland, it has also been shown that the presence of fish led to hypoxic conditions during grow-out but no hypoxic conditions during the fallowing period of the same site the following year (Burt el al., 2011). It was also shown that the hypoxic events were intermittent but they could occur for two and a half months to varying degrees for different sites (Burt et al. 2011). Therefore, if a site has a short period where currents are absent, a large biomass of fish is present, temperature is high and dissolved oxygen low, a mass mortality event could unfold.

Models will be crucial in the future development of the aquaculture industry and areas where culture takes place. The previously mentioned models are baseline models and consider factors such as; biofouling organisms on the nets, phytoplankton blooms, fish feces, sediment, oxygen input from air-sea, congregation of other organisms in and around sea-cages, massive freshwater runoff, which will all have an impact of final estimation of indices (Chang et al, 2009).

Through the use of models, past and current data, cases similar to the example where the site was reoriented in Newfoundland, may need to be applied to other areas identified throughout the Atlantic zone. This can be accomplished by the physical profiling of high culture zones and surrounding areas with the subsequent development of trends and projections for future reference. Alternative measures may have to be utilized to combat problems such as low oxygen levels or low water temperatures leading to sea-ice cover. For example, in Nova Scotia, Newfoundland and New Brunswick aeration units may be deployed at sites to increase oxygen levels during hypoxic periods. This may be during peak temperatures in summer months, while feeding fish or during slack tide when the inflow of oxygen rich water has halted for that tidal cycle (Area Managers, pers. comm.). In Newfoundland, some areas have a high influx of fresh water causing some major farming areas to be completely covered with sea ice during the winter months. One solution to this problem is also the use of aerators to agitate the water, inhibiting the water from freezing over. This was one major problem for growers in Newfoundland, but with the improvement of culture technology, sites have been moved further from these areas to locations that are free of sea-ice year round.

One final issue that needs to be considered for salmon is the treatment of sea-lice with hydrogen peroxide and other therapeutants. Sea lice continue to be one of the major issues faced by salmon farmers and is directly linked to environmental conditions for various life stages and when it can be treated. The treatment period is temperature regulated as acute lethal toxicity increases with temperature and exposure time. It is recommended that hydrogen peroxide treatments only be applied at temperatures up to 14 °C (Thomassen, 1993; Kiemer and Black, 1997) with treatments past this threshold being very sensitive and can result in mortality. If water temperatures increase in the spring and summer at rapid rates, due to climate change, it may result in a decreased period of time where safe delousing treatments can be applied. If the rate of temperature increase is gradual, it may result in an increased period where treatments can be applied. These are the types of issues that need to be considered by the industry and adapted to as it moves forward in a continually changing environment.

6.4.2 Steelhead Trout (*Oncorhynchus mykiss*)

Steelhead trout is the anadromous rainbow trout that is grown in salt water during later stages of life (Dubé and Mason, 1995). Rainbow trout follow a similar life cycle as Atlantic salmon, although after they smolt and begin their life in salt water, they are considered steelhead trout. In the past, steelhead trout have been grown in sea cages in Newfoundland, Nova Scotia and New Brunswick, but are currently cultured in Nova Scotia (Appendix 6.1, Fig. 6–4) and Newfoundland only.

Smoltification occurs when fish range from 12-22 cm in length and are placed in full saline water (Sedgwick 1973; Pennell and Barton, 1996). Genetic makeup can also have an influence on the toleration to sea water, with some strains being more tolerant than others (Sedgwick, 1973). Steelhead can be grown both in fresh and salt water but there are a number of advantages to growing them in salt water. The key advantage of growing steelhead trout in sea water is the warmer water temperature present in the ocean for a prolonged period of time during the fall and winter seasons compared to fresh water. This results in a prolonged period in which the trout can be fed and will eat, resulting in an increased growth rate (3–4 times greater) compared to fresh water (Sedgwick, 1973; Teskeredžić et al.1989). Steelhead trout survive in temperatures ranging between 0–23.9 °C (Pennell and Barton, 1996) with an optimal growing temperature for post-smolts of 16 °C and adults (approximately 4 kg) ranging between 10–22 °C (Pennell and Barton, 1996; Hill, 1992) with wild trout dwelling mainly in areas not exceeding 21 °C during peak temperate periods (Dube and Mason, 1995). It has been shown that steelhead do osmoregulate reasonably well at low temperatures, moreover holding fish at temperatures ≤ 0 °C has a high risk of mortality with the lower lethal limit being -0.7 °C for steelhead trout (Saunders et al. 1975). Other environmental parameters for steelhead production are similar to Atlantic salmon as well (See Appendix 6.2, Table 6–4).

Steelhead, like Atlantic salmon will also be subjected to hypoxic events when reared in sea cages so the chronic lower limit of 6–6.5 mg/L is the minimum oxygen saturation level to maintain and prevent mortality (Dube and Mason, 1995; Pennell and Barton, 1996; Mansour et al, 2008; Chang et al, 2009; Burt et al, 2011). Oxygen saturation of > 8 mg/L is accepted by the industry as the optimal for salmonid culture (Forsberg and Bergheim, 1996; Pennell and Barton, 1996; Thorarensen and Farrell 2011).

Salinity is not usually considered as a critical factor in steelhead culture because the fish are anadromous. The preferred range for steelhead culture is between

18-33 ppt but the fish are able to tolerate fresh water (Macleod, 1977; Hill, 1992; Pennell and Barton, 1996) similar to a number of other salmonid species.

As CO_2 emissions increase, freshwater and ocean pH will decrease and this can have an affect on various life stages of steelhead and other salmonids. This is more of an issue for land based or pond culture but can still have an effect in the ocean. The optimal pH range for adult steelhead is between 6.5–8.0 in both fresh and salt water (Pennell and Barton, 1996).

Overall, there is a limited amount of literature on steelhead culture practices in sea water compared to other salmonids such as Atlantic salmon. It is accepted by scientists and industry that the major environmental parameters such as temperature, oxygen, salinity, pH (Saunders et al. 1975; Hill, 1992; Dube and Mason, 1995; Pennell and Barton, 1996) and any issues regarding climate change affecting Atlantic salmon are also a concern for steelhead trout as the two species have similar environmental parameter thresholds when reared in the open ocean.

6.4.3 Arctic Charr (*Salvelinus alpinus*)

The commercial production of Arctic charr began in 1981–1984 in Newfoundland and Labrador. The majority of Arctic charr culture occurs in fresh water lakes and in facilities using both fresh and brackish water. In New Brunswick, charr have been raised experimentally since 1985 and commercially since 1987. The majority of the production comes from freshwater operations with some experimental trials in saltwater contributing to the total production. Today in Atlantic Canada, there is only one marine cage site operating in New Brunswick's Bay of Fundy and one in Newfoundland (Delabbio, 1995; B. Glebe, pers. comm.). The remaining charr operations, like the past, are in fresh and brackish water facilities in Nova Scotia and New Brunswick.

Arctic charr are part of the salmonid family and have environmental thresholds that are within the range of other salmonids (See Appendix 6.2 Table 6–5). Charr dwell in temperatures ranging from 0–23 °C with the optimum temperature for growth ranging from 6 °C to 15 °C (Johnston, 2002). When Arctic charr were held in a stratified sea cage with temperature range of 4–18 °C, they chose to occupy a temperature range of 12–15 °C (Sutterlin and Stevens, 1992). The upper limit for feeding and growth of charr is 21.5 °C with the upper lethal limit being > 23 °C (Johnston, 2002). Arctic charr do cope relatively well with low temperatures and it has been shown that they can grow approximately 1% per day at temperatures between 0.5 °C and 4 °C. Fish stop feeding at approximately 0 °C and growth is inhibited at 0.3 °C (Johnston, 2002).

Oxygen saturation is another environmental parameter for Arctic charr that is similar to Atlantic salmon. Charr prefer oxygen saturation of 6.5–8.5 mg/L or more for ideal growth and survival, which is similar to other salmonids (Johnston, 2002). If oxygen saturation falls below 65-70%, Arctic charr experience a reduced efficiency in oxygen transfer. They can tolerate levels of 5 mg/L but this results in poor growth and anything lower than this will result in mortality (Johnston, 2002) .

Increasing levels of CO_2 in the water lowers pH, which will also lower the blood pH of Arctic charr. As blood pH decreases in a fish, it lowers the O_2 binding affinity that can lead to mortality (Johnston, 2002). The majority of fish, including Arctic charr, can tolerate a pH between 5-9 with the maximum productivity ranging between 6.5-8.5 (Jobling, 1994). Lethal limits for char are < 4 and > 11 (Johnston, 2002). As pH decreases it also increases the solubility of trace metals in the water that can become toxic to fish (Johnston, 2002).

Salinity is one physiological aspect for Arctic charr that differs from other anadromous salmonids. The difference when compared to other salmonids is that charr cannot tolerate full saline water year round (Johnston, 2002), especially in the winter months. Arctic charr are amphihaline, which means they only have a seasonal tolerance to saline waters (Johnstone, 2002) unlike Atlantic salmon that can survive for years in full saline water. Charr normally enter the ocean in mid-to-late June to feed and return in mid-August to early September. They need to be approximately 15cm in length to handle full saline waters and in some cases, first time smolting fish will only spend 2–3 days in the ocean before returning to fresh water (Johnston, 2002). Arctic charr can survive in salinities ranging from 0–35 ppt, with the optimal survival range being 10–35 ppt and ≤ 15 ppt yielding the highest growth (Johnston, 2002).

The majority of Arctic charr culture takes place in closed containment systems on land as a result of their inability to tolerate full saline water year round. When being cultured in the marine environment, sea cages are usually located in bays containing brackish water. These bays may experience periodical influxes of full saline water but for the majority of the time, the water remains brackish. Environmental parameters such as salinity, temperature, oxygen and pH are very important for charr culture, and with a changing environment it may be lower risk and more economical to culture charr in closed containment systems where optimal rearing conditions can be maintained and controlled to produce a high quality product in a minimal amount of time.

6.4.4 Atlantic Cod (*Gadus morhua*)

Atlantic cod is a marine gadoid that lives in waters ranging from Greenland to Cape Hatteras, North Carolina, with the highest densities being found around Newfoundland, in the Gulf of St. Lawrence, on the Scotian Shelf and Georges Bank (Fahay et al., 1999). Currently, cod culture takes place in Canada (New Brunswick (Appendix 6.1, Fig. 6–1. Site# MF-0034, and Newfoundland), Norway, Iceland, Ireland and the Faroe Islands and the United States (Bolton-Warberg and Fitzgerald, 2012; http://www.aquaculture.ca/files/species-atlantic-cod.php).

Within their geographic range, cod can survive in waters that are approximately -1.7 to 20 °C but are mainly found in 0- 12 °C (Fahay et al, 1999; Fletcher et al., 1997; Drinkwater, 2005) (See Appendix 6.2 Table 6–6). Cod will feed at temperatures as low as 0 °C and as high as 17 °C (McKenzie, 1934, 1938). As

Atlantic cod body size increases, optimal temperature for growth decreases (Imsland et al., 2005). Optimal growth is achieved at 11-15 °C for smaller cod (5-800 g) and 7–12 °C for larger cod (Björnsson et al., 2001; Schurmann and Steffensen, 1992; Imsland et al., 2005; Pedersen and Jobling, 1989). Growth rates vary based on geographic location, and through the use of models, it can be predicted what size fish should be put in sea cages for culture and how long it will take to reach a market size. It has been shown that a 250 g fish should be stocked in Northeast Iceland and Western Norway in May, which will result in a 3,434 g and 3,684 g fish respectively in two years (Björnsson et al., 2007). If a 30 g fish is stocked in these two localities the difference will be 24% in size when they reach the two-year mark in the sea cage (Björnsson et al., 2007). This model can be applied to Canadian waters, but for this particular study, only incorporated two locations (Iceland and Norway). This is an important study, as it shows how to separate geographic locations can produce different size fish over a certain period by manipulating size at stocking. This is the type of model needed to identify optimal areas for culture of cod and determine if it will be economical or not to pursue cod culture in certain areas.

Salinity is another environmental parameter that is geographically driven and important for optimal growth and survival of Atlantic cod. Cod are able to tolerate low salinities and have been found in brackish waters throughout their geographic range. It has been shown that cod can tolerate salinities as low as 7 ppt (Dutil et al., 1992) but mortality occurs at 3 ppt (Odense et al., 1966). Growth is higher in lower saline waters compared to higher saline waters as a result of increased food assimilation, digestion efficiency and decreased osmotic regulation (Lambert et al., 1994). In an experiment comparing growth in various salinities, cod growth was higher at 7 ppt and 14 ppt compared to 28 ppt (Lambert et al., 1994). Therefore, salinity changes due to climate change are not of great concern for the cod aquaculture industry. One consideration may be to identify areas with lower salinity for cod culture to take advantage of higher growth under these conditions.

Oxygen is very important in the survival and growth of Atlantic cod. The low threshold for survival is < 20% O_2 saturation in a temperature range of 2-10 °C. (Chabot and Claireaux, 2008; Plante et al, 1998). Growth and ingestion is significantly reduced when dissolved oxygen decreases to 50% saturation (Chabot and Claireaux, 2008). It has been shown that the LC_{50} for oxygen saturation is between 21-28% (at 2-6 °C) during 96-hour exposure and that the LC_{50} for a 3-hour exposure is 9% saturation (at 2-6 °C) (Plante et al, 1998), showing that cod can tolerate short term, low oxygen levels. As temperature decreases, so does the lethal oxygen saturation level. For temperatures of 5, 9, 10, 11, 15 and 17 °C, the lethal oxygen saturation limits were 5, 11, 14, 15.5, 16.5 and 29% respectively (Schurmann and Steffensen, 1992). For growth parameters, it has been shown that growth with respect to length begins to be affected at 65% oxygen saturation, and significantly at 56% saturation (Chabot and Dutil, 1999). Mass, and thus calculated condition factor, begin to be affected when oxygen saturation decreases to 73% and significantly at < 65% (Chabot and Dutil, 1999). When oxygen begins to reach low levels, growth is severely inhibited. For example, when comparing 45% oxygen saturation to normoxic conditions, length was reduced by 36%, mass by 56%, condition factor was changed by 64% and liver indices were changed by 30% (Chabot and Dutil, 1999). Therefore, it is very important that cod be cultured in optimal areas of high oxygen in order to produce a high quality product in the shortest period of time.

Ocean acidification and decreasing pH is a concern for the early life stages of Atlantic cod, more so than adult stages. It has been shown that cod larvae are affected by decreases in pH (Frommel et al., 2012) but larger animals are able to regulate their acid-base balances (Gilmour et al., 2009; Perry and Gilmour, 2006) therefore, pH decreases are not of imminent concern for the sea cage grow-out phase of Atlantic cod culture.

Atlantic cod is an aquaculture species that is still in the early stages of commercialization compared to species such as Atlantic salmon. Optimal production protocols are still being developed for both larval and adult stages of life. More work has been conducted on the early life stages in relation to commercial production as well as climate change and various environmental conditions, but little has been conducted on larger animals in sea cages. More studies on larger fish or studies at a commercial scale need to be conducted to better understand how this fish is going to respond to a changing climate.

6.4.5 Blue Mussel (*Mytilus edulis*)

In Atlantic Canada, most mussel culture is conducted using suspension culture in Prince Edward Island (Appendix 6.1, Fig. 6–5), but it is also cultured in various coastal areas of each of the Atlantic Provinces (Newfoundland and Labrador, Appendix 6.1, Fig. 6–2; New Brunswick, Appendix 6.1, Fig. 6–7; Nova Scotia, Appendix 6.1, Fig. 6–8). Mussel culture in Atlantic Canada became established in the late 1970's as a result of optimal environmental conditions, abundant seed supply and combined efforts between government and private sectors (Mallet and Myrand, 1995). It has grown considerably over the years from 1000 t being produced in 1980 (Mallet and Myrand, 1995) to approximately 24,000 t being produced during 2010 in Atlantic Canada and Quebec (Table 6–2).

Blue mussel aquaculture can be conducted in various ways such as; suspended culture (longlines or rafts), or bottom culture and using "bouchots" where mussels are attached to large wooden stakes placed in the intertidal zone. Mussel culture begins in late May and early June that is the spawning season for blue mussels. Larvae are free swimming for three to four weeks upon which they settle to the bottom or on a suitable substrate and are considered juveniles (Mallet and Myrand, 1995). September-December is when juvenile mussels (5-30mm), referred to as seed/spat by the industry, are stripped from collectors and are placed in "sleeves" or "socks" where they re-attach to the long-lines to continue growth to a market size (Mallet and Myrand, 1995). There are two main factors that result in optimal production of mussels. The first factor is density that can be controlled by farmers to produce a high quality product in as minimal amount of time as possible. The second factor is the environment and a number of different parameters that, once the site is selected, are out of the control of farmers. Sites for mussel culture have been selected in areas that have optimal environmental conditions for growth and production (See Appendix 6.2, Table 6–7). As climate change further warms oceans, prime culture sites may change and industry will need to explore and identify new areas that will contain optimal environmental growth conditions.

Larvae and juvenile mussels can tolerate temperatures between 3–25 °C (Coulthard, 1929; Brenko and Calabrese, 1969; Bayne 1976; Gonzalez and Yevich, 1976 Almada-Villela et al., 1982) and adult mussels can withstand temperatures as low as -1.5 °C. The upper lethal limit for larvae, juveniles and adults is 27 °C–28 °C (Gonzalez and Yevich, 1976; Mallet et al, 1990; Mallet and Myrand, 1995) and it has been shown that temperatures above ≥ 20 °C should be avoided as it is associated with incidence of summer mortality (Coulthard, 1929; Gonzalez and Yevich, 1976; Incze et al, 1980; Newell, 1989; Mallet and Myrand, 1995). One study has shown that the upper lethal temperature limit for mussels was 29.8 °C in June (Jones et al., 2009) and that mussels can tolerate higher temperatures for longer in the warmer summer months (Chapple et al., 1998) when acclimated to high temperatures. Mussels can withstand a wide temperature range but growth is optimal at temperatures ranging between 15 °C to 20 °C in salinities ranging between 20-35 ppt (Coulthard, 1929; Brenko and Calabrese, 1969; Bayne 1976). Growth declines sharply at temperatures > 20 °C and is severely depressed above 25 °C (Brenko and Calabrese, 1969; Gonzalez and Yevich, 1976). Mussel growth also declines sharply below 10 °C but it has been shown they can still grow between 3 °C and 5 °C (although minimally) (Almada-Villela et al., 1982). Temperatures vary from one location to another that can result in some areas producing market sized mussels in a shorter period of time compared to others.

Many areas in Atlantic Canada, like the eastern coast of Nova Scotia, have full saline water (> 30 ppt) which produces a slower growing mussel compared to areas like Prince Edward Island (PEI) which has lower saline waters (25-30 ppt) (Mallet and Myrand, 1995). Mussels can tolerate salinities ranging from 0-40 ppt (Brenko and Lalabrese, 1969; Stewart, 1994; Bayne 1976). The minimal salinity limit that mussels can survive in for prolonged periods of time is 15 ppt (Stewart, 1994; Bøhle, 1972) with very little growth. If salinity remains low, mussels will close their shells to avoid the low saline waters which may come in the form of pulses of fresh water from rain storms or runoff from shores after a storm or spring melt. Levels of ≥ 18 ppt produce acceptable growth rates with 26 ppt being the optimal salinity level for growth (Mallet and Myrand, 1995). This is why the majority of mussels produced in Atlantic Canada are from PEI.

Oxygen saturation is another environmental parameter that is a concern for mussel growers. Compared to high temperature issues, oxygen is not as big an issue because mussels have a mechanism to deal with low oxygen. Naturally occurring wild mussels can be found in the intertidal zones. At low tide, when some mussels may be out of water and exposed to air, they close their shells and use metabolic systems that do not require oxygen (Stewart, 1994). Mussels can acclimate to approximately 50% oxygen saturation but past this point is when they will close their shells to avoid the hypoxic conditions (Stewart, 1994).

A decrease in ocean pH is another issue that threatens the production of mussels in the Atlantic. As a result of human CO_2 emissions, ocean pH has begun to decrease and will continue to decrease. The oceanic sink accounts for approximately 48% of the anthropogenic CO_2 emissions (Sabien et al 2004) and as the CO_2 dissolves in the ocean, the pH decreases (Calderia and Wickett, 2003). This reduction in pH could have negative impacts for bivalves and their shell growth and integrity (Fabry et al, 2008; Royal Society, 2005). It has been shown that there is little to no growth in large and small mussels at pH of 6.7 and no difference in growth between pH 7.4-8.1 (Berg et al. 2006). There is no difference in growth between pH 7.4 and pH 7.6, therefore, the threshold for effect on growth is between pH 7.1-7.4 (Berg et al. 2006). Shell integrity is very important for bivalves, as the shell protects against predators as well as against unfavourable environmental conditions when they arise. If shells become weak, leaving them susceptible to predators and poor environmental conditions, mass mortality events could occur and be very detrimental to farmers and the industry (Royal Society, 2005; Fabry et al, 2008). These are very important factors that need to be considered by the industry and should be the focus of future research.

6.4.6 The American Oyster (*Crassostrea virginica*)

The American oyster, also known as the Eastern, Atlantic, and Malpeque oyster, is one of the main shellfish species cultured in the Atlantic zone. Oyster culture takes place mainly in the Gulf of St. Lawrence along the coasts of northern New Brunswick (Appendix 6.1, Fig. 6–6), southern Prince Edward Islands and Nova Scotia (Appendix 6.1, Fig. 6–9) (http://www.aquaculture.ca/files/species-oysters.php). Oyster culture began in PEI during 1865 and expanded to New Brunswick and Nova Scotia (Lavoie, 1995). In 2009, PEI produced 31%, New Brunswick 25% and Nova Scotia 4% of the total oysters produced in Canada, which was approximately $20 million in market value (Table 6–2).

Similar to blue mussels, oysters will close their shells under unfavourable temperature, salinity, and anoxic conditions (See Appendix 6.2 Table 6–8). Oysters have been cultured in a number of ways in the past, but the main techniques used today are either "planting" or "seeding" the bottom with oyster seed or through the use of floating bags that are suspended in the water column. 'Planting' the bottom is where oyster larvae are collected from the wild or from hatcheries, held in tanks until they transform into seed (small juvenile oysters) and reach a size where they can be transferred into the ocean. Once they reach an acceptable size, they are placed on the sea floor in ideal habitat areas where they will grow to a marketable size. The other form of culture more farmers are using today is floating bag or cage systems, as they are easy to access and have a lower predation rate compared to oysters on the bottom. Once the oysters reach an acceptable size they are placed in bags or cages that are suspended in the water column. There are a number of different types of bags/cages but they follow the same concept where they are off the bottom and can be raised or lowered to specific depths with relative ease. Oyster farming is a lucrative industry for the Maritime Provinces that merits the monitoring of the environmental parameters that could influence its continued success, particularly in the context of climate change.

As with other aquaculture species, temperature is an important factor that determines the survival and growth of oysters. Oysters are subject to temperatures ranging between -2 °C to 36 °C within their geographic range and in some areas at low tide have survived temperatures reaching 49 °C for a short duration (Galtsoff, 1964; Communications Branch Fisheries and Oceans Canada Cat No: Fs 41-33/14-1993E; Shumway, 1996). The optimal temperature for the growth of adult oysters ranges between 10–20 °C (Loosnaoff, 1958; Shumway, 1996; Pernet et al. 2007) and for embryonic development between 20-30 °C (MacInnes and Calabrese 1979) with embryonic abnormalities occurring above and below this range. Oysters grow at temperatures above 9 °C, stop feeding when temperatures reach 4 °C and are quiescent at 0 °C (Loosanoff, 1958; Shumway, 1996; Pernet et al. 2007). In the Gulf of St. Lawrence, where the majority of oyster culture takes place, phytoplankton blooms occur at temperatures ranging between 4 °C to 9 °C during autumn and spring, which is below the optimal temperature range for growth (Comeau et al. 2008; Pernet et al. 2007). As climate change warms this region, it could lead to an increased production period needed for oysters to reach a market size, if temperatures remain in this lower range for an extended period of time. Climate change could also benefit farmers by decreasing the production time, if sea water temperatures begin to rise which will result in an increased growth rate for oysters (Comeau et al. 2008). Increased sea water temperatures could also lead to an expansion of the geographic area, in a northerly direction, where oysters could be cultured.

Salinity is another environmental factor that influences growth of oysters. Low salinity can lead to mortality events as well as inhibit feeding, growth and spawning. Oysters can feed at salinities as low as 5 ppt, not below ≤ 3 ppt and feeding is unaffected at ≥ 12 ppt (Loosanoff, 1952). Oysters are not common in areas of constant low salinities of ≤ 5 ppt but it has been reported that oysters can survive at salinities of 2 ppt or less for a month if water temperatures are low (Shumway, 1996). The optimal range for growth is between 14 to 28 ppt (Galtsoff, 1964; Shumway, 1996), which can vary according to geographic location. Salinities of 10 to 20 ppt with an average of 15 ppt tend to be within the optimal range for reproduction, as populations are dense and old oyster shells create ideal areas for spatfall (Shumway, 1996). Normal embryonic development occurs between 16-30 ppt (MacInnes and Calabrese 1979) but larvae can tolerate salinities from 3-31 ppt (Carriker, 1951). For recently set oysters, it has been shown that the optimal salinity for growth was between 15 to 22.5 ppt (Shumway, 1996). Overall oysters can survive a wide range of salinities between 0-40 ppt (Galtsoff, 1964) but between the optimal range of 12-28 ppt a narrower physiological optimal range of 15-18 ppt exists (Loosanoff, 1952; Shumway, 1996).

Particularly in estuarine environments during summer months, hypoxia is a common issue that can be very stressful on oysters. It has been shown that oysters can survive for 5 days in water containing less than 1.0 mg/L of dissolved oxygen (Sparks et al. 1958) and that oxygen consumption increases with decreasing salinity (Shumway and Koehn, 1982). Hypoxia (1.5 mg/L) for oysters will also delay the development of the larvae, which prefer normoxic conditions of 7.3 mg/L (Baker and Mann, 1994). Hypoxia is not the only issue for the warmer summer months as elevated CO_2, which causes a lower pH, is often associated with hypoxic conditions (Boyd and Burnett, 1999). It has been shown that a reduction in pH and oxygen will reduce the production of reactive oxygen intermediates (ROIs) by 33% compared to normoxic conditions. ROIs are part of an important cellular mechanism used to defend against bacteria, viruses, and protozoa's (Boyd and Burnett, 1999). If ROIs are decreased as a result of environmental conditions, it could lead to mass mortality events for the industry. In past experiments, a pH range of 7.8–8.0 has been used for experimental purposes and considered normoxic. It has been shown that oysters will pump water at a pH of 4.25, but it is significantly lower than controls (Shumway, 1996). Oysters will spawn between pH 7.8–8.2 in Long Island Sound and not below a pH 6.0 or above pH 10 (Calabrese and Davis, 1966). Normal embryonic development occurs between pH 6.75–8.75 with the lower lethal limit for larvae being 6.0 (Calabrese and Davis, 1966; Shumway, 1996). The optimal pH for growth of oyster larvae is between 8.25–8.50, with growth decreasing rapidly below pH 6.75 (Calabrese and Davis, 1966; Shumway, 1996).

Oyster growth and survival are affected by the environmental parameters; temperature, salinity, oxygen and pH. Oyster culture declined in Canada between 2006 and 2009 with total production being 12,488 tonnes and 8,525 tonnes respectively (Communications Branch Fisheries and Oceans Canada Cat. No.: Fs49-9/2011; Communications Branch Fisheries and Oceans Canada Cat. No.: Fs1-15/2006). Losses have been due to severe weather events as well as from the parasite Multinucleate Sphere X (MSX) that can also be influenced by climate change (Ewart and Ford, 1993). Climate change may have more of an affect on certain life stages of oysters and may be positive for some life stages but negative for others. We have control of the more fragile, early life stages of Atlantic salmon or steelhead trout in hatcheries and are able to transfer them during a hardier point in their life cycle in to the natural environment. Early life stages of shellfish such as oysters and mussels may be more susceptible to climate change and environmental fluctuations. These early life concerns need to be addressed in future research to help us understand the potential impact of climate change on this species.

6.5 SUMMARY OF DIRECT AND INDIRECT EFFECTS OF CLIMATE CHANGE ON MARINE AQUACULTURE IN ATLANTIC CANADA AND QUEBEC

6.5.1 Direct Effects

6.5.1.1 Temperature

Temperature is one of the most important environmental parameters driving aquaculture production. It has been shown that most areas in the Atlantic Basin supporting aquaculture (Bay of Fundy, Gulf of St. Lawrence, St. Lawrence Estuary, and Newfoundland coast) have revealed a warming trend in surface water temperature over the past century of 1–2 °C (Loder et al, 2013; Sherman and Lentz, 2010). A gradual warming may result in the optimal growth period as well as the growing season being prolonged or shortened, depending on the species and their geographic distribution. Any increase and/or decrease of temperature would have a significant influence on aquatic animal metabolism and hence growth rate and therefore total production. In addition to optimal growing seasons being extended or shortened (species specific), the geographic ranges for culture may be extended or narrowed depending on location.

6.5.1.2 Salinity

Shallow bays and estuaries are subjected to pulses of freshwater from land and river runoff. This can decrease the salinity in the area, but may not be a significant issue for certain aquaculture species. Salmonids are anadromous and can tolerate salinity fluctuations in the marine environment. The majority of salmonids can tolerate full saline waters year round except for Arctic charr (*Salvelinus alpinus*) (Johnston, 2002). Gadoids, such as the Atlantic cod (*Gadus morhua*), can tolerate lower saline, brackish waters. It has been shown that they have higher growth performance in lower salinities but fresh water is lethal (Lambert et al., 1994). Shellfish, such as blue mussels (*Mytilus edulis*) and American oysters (*Crassostrea virginica*) can also tolerate low saline, brackish waters for short periods of time. This is one characteristic that farmers take advantage of when growing shellfish in estuaries, and if freshwater pulses are prolonged, mussels and oysters will close their shells until the salinity returns to more favourable conditions. One exception to this is the sea scallop (Placopecten magellanicus), which is far less tolerant to low salinity waters. According to Hart and Chute 2004, all life stages of sea scallop were rare or absent in the mixing zone of New England bays and estuaries, but abundant in full-strength seawater, with adults having a lower lethal threshold of 16.5 ppt.

6.5.1.3 Dissolved oxygen

Dissolved oxygen has been decreasing in all areas of the Atlantic Basin and is projected to continue decreasing. This decrease is associated with a number of mechanisms, with stratification of the oceans being the most common (Garcia and Keeling, 2002). As temperature increases, oxygen concentration decreases and vice versa (Schurmann and Steffensen 1992). Decreases in oxygen can lead to hypoxic events that can severely stress or kill fish and shellfish. Geographic area plays a very important role in oxygen saturation. For example, areas that are shallow, have low current velocity and low water mixing will most likely have low oxygen saturation compared to areas of high currents and mixing. Newfoundland is characterized by aquaculture sites that are high in oxygen as a result of oxygen rich upwelling waters from deeper depths compared to other areas, such as shallow coastal bays around Prince Edward Island.

6.5.1.4 Acidity

Elevations in atmospheric CO_2 have been associated with a decline in pH of our oceans (Calderia and Wickett, 2003) that can have a number of negative impacts on aquaculture species including disruption of physiology (e.g., acid-base regulation, respiration, growth, hatch rate, calcification) (Gazeau et al. 2010; Fabry et al., 2008; Royal Society, 2005; Riebesell et al. 2000). It has been shown, mainly for freshwater species, that sensitivity to acidification reduces with increasing body mass (Robinson et al. 1976; Rask, 1984). Therefore, for finfish species for which larviculture occurs in controlled land-based systems, there is less concern for environmental changes associated with climate change as water quality parameters can be monitored and controlled during these sensitive stages. Decreased pH makes bivalves susceptible to bacteria and viruses (Boyd and Burnett, 1999). For calcifying species, hatch rates are reduced (Gazeau et al. 2010), shell growth and integrity are also threatened, leaving them susceptible to predators (Royal Society, 2005; Fabry et al., 2008). Some farmers are moving to holding earlier life stages of shellfish in closed containment systems similar to finfish, but this is costly for species that have a low market value.

6.5.2 Indirect Effects

6.5.2.1 Disease and parasites

There are a number of viruses and parasites that have an impact on aquaculture species, and as environmental conditions change, the proliferation of these diseases and parasites may increase or decrease. Viruses and parasites can be transferred horizontally in a number of ways; through direct contact with infected fish in the water column, from water currents carrying pathogens from infected fish to uninfected sites, as well as from site boats and workers who have not properly disinfected upon entering an uninfected site. Vertical transmission is also possible for some pathogens, where the infected parent passes the virus onto their offspring. Infectious salmon anemias (ISA), infectious pancreatic necrosis (IPNV), infectious haematopoietic necrosis (IHN), Furunculosis, Viral hemorrhagic septicaemia virus (VHSV), Haplosporidium nelsoni (MSX), Bacterial kidney disease (BKD), *Lepeophtheirus salmonis*, Caligus elongates, and Vibriosis are all viruses and parasites that can be very detrimental to finfish and shellfish aquaculture farms if they become infected (Falk et al, 1997; Mortensen et al, 1998; Hofmann et al. 2001; Johnston, 2002; World Organisation for Animal Health, 2009). These pathogens have infected fish and shellfish farms in areas along the eastern coast of Canada, with some being more devastating than others. The temperature range in which these viruses and parasites can survive is within the survival temperature range of the aquaculture species and in some cases; the viruses can survive in extremes where the fish and shellfish cannot.

Therefore, as waters warm, viruses and parasitic geographic regions will expand but also peak proliferation times will be maintained for prolonged periods of time, increasing organism susceptibility and infection rates. For example, the ISA virus has its highest proliferation rate at 15 °C, but proliferation is reduced at 20 °C and inhibited at 25 °C (Falk et al, 1997). It has been shown, that waters in the Bay of Fundy between 1990 and 1995 reached average temperatures between 12-16 °C from July to September, with peak temperatures of 16 °C being observed in August (Robinson, et al, 1996). If these temperatures are reached earlier in the year and prolonged into later months, as a result of climate change, then salmon sites in the Bay of Fundy will be at a higher risk of ISA infection compared to the past and cooler temperate years.

One of the current major concerns for salmon farmers is the spread of the ectoparasites *Lepeophtheirus salmonis* and *Caligus elongates* (sea lice), which are the two common marine ectoparasites present in the Northwest Atlantic that affect salmonid aquaculture, with L. salmonis being the more common of the two (Johnson and Albright, 1991). It has been shown that females can produce approximately 10 egg strings of varying sizes in a season (Mustafa et al., 2000). It was once thought that sea lice could not reproduce throughout the winter but the eggs can hatch and develop between 2 °C and 10 °C but probably need ≥ 4 °C to complete their lifecycle (Boxaspen and Naess, 2000). Overall, temperature increases will reduce the time to complete the entire life-cycle of the sea louse, increasing their productivity, which will have negative impacts on salmon aquaculture (Stien et al., 2005). It has been shown that cooler waters of the winter months have a lower incidence of infection, so as waters warm, which were once lower in temperature; infestation pressure on farms will increase, as well as expand the geographical distribution of hosts and parasites (Heuch et al. 2002, Rikardsen, 2004). As infection rates rise, the fish are more susceptible to secondary infections, osmotic problems, reduced appetite and changes in haematological parameters (Boxaspen, 2006). These parameters all impact the final product and profits for farmers, and are of great concern in the changing environment.

Another parasite, *Haplosporidium nelsoni* (Multinucleate Sphere X, MSX) is a parasite that has killed large numbers of oysters along the east coast of the United States and is spreading northwards, with reports of the disease in the Bras d'Or Lakes (Cape Breton, Nova Scotia) but with no reports of detection between Maine (United States) and the Bras d'Or Lakes (Stephenson et al. 2003). The spread of MSX is believed to be a result of climate warming. The presence and intensity of MSX is seasonally driven, with temperature, salinity and food availability being the main influential factors (Hofmann et al. 2001). Oysters are infected in May-June, reaching maximum intensity in the fall. A decrease normally occurs in winter as a result of low winter temperatures killing oysters that are infected as well as the parasite itself (Hofmann et al. 2001). The overall spread of MSX is not entirely known, but through the use of models and past observations, it is believed that warming temperatures, especially in winter, enables MSX to stay in areas where it is already established and continue to spread northwards as waters begin to warm (Hofmann et al. 2001).

Overall, each virus and parasite is different and should be viewed individually on their potential impact on aquaculture in the future. Some are affected by temperature changes, pH, and salinity but the spread of the sea lice and MSX parasites are a primary concern of the aquaculture industry, as well as rising temperatures that will increase the proliferation rate of diseases already present in farmed geographic locations.

6.5.2.2 Harmful algal blooms

Increases in shellfish poisoning events with climate change need to be considered as temperature, salinity, nutrient concentration and precipitation contribute to algae blooms (Martin et al. 1998). The algae produce toxins that are harmful to humans, the mussels consume the algae and the toxins accumulate in their tissues. Humans will in turn, consume the mussels and this can be lethal for humans (Mallet and Myrand, 1995; Martin et al, 2001). There are more than 150 species of phytoplankton observed in the Bay of Fundy (Martin et al, 2001) and there are approximately 10 species in Atlantic waters that can produce lethal toxins (Mallet and Myrand, 1995). The main types of shellfish poisoning occurring in Atlantic Canada are (i) paralytic shellfish poisoning (PSP), caused by *Alexandrium fundyense* which are found throughout Atlantic Canada (Mallet and Myrand, 1995), (ii) diarrhetic shellfish poisoning (DSP), which is caused by species of Dinophysis or Prorocentrum, found mainly on the Atlantic coast of Nova Scotia (Mallet and Myrand, 1995) and (iii) amnesic shellfish poisoning (ASP), which is caused by *Nitzschia pungens* which are found mainly around Prince Edward Island and the Bay of Fundy (Mallet and Myrand, 1995). Fisheries and Oceans Canada and provincial governments have programs in place to monitor the distribution and abundance of the algae to ensure safe, non-contaminated mussels are being sold (Mallet and Myrand, 1995). This can result in closure of certain sites during specific times of year, and as environmental conditions/trends transform as a result of climate change, it could lead to longer periods of time when mussel farmers are inhibited from marketing their product.

In addition to the increased risk of toxic events, eutrophication and algae blooms could also result in hypoxic conditions and mass mortality events if farmers are not careful and aware of the marine conditions.

6.5.2.3 Food availability

Changes in sea surface temperatures and other oceanographic variables (wind velocity, currents and wave action) may decrease flushing rates and affect food availability to shellfish. There may also be changes in abundance and/or the range of capture fishery species used in the production of fishmeal and fish oil (Handisyde et al. 2006). Canadian salmon farmers use an average of 30 percent fishmeal and oil in their feed, whereas these are the main ingredients in feed for Arctic Char and Atlantic Cod (CAIA http://www.aquaculture.ca/files/species-salmon.php).

6.5.2.4 Infrastructure damage

There is no evidence of an increase in the frequency or intensity of storms, but intense storms lead to structural damage, and an increase could lead to enhanced damage, an introduction of disease or predators during flood episodes, and an increase in escapees (leading to the potential for negative cultured/wild stock interactions) (Handisyde et al. 2006).

6.6 KNOWLEDGE GAPS AND FUTURE RESEARCH CONSIDERATIONS

6.6.1 Salmonids

- Temperature, oxygen, pH and salinity profiles for various geographic locations in conjunction with trends and projections and larger scale models
- Sea lice research, ecology, physiology and proliferation
- Spread of pathogens in relation to climate change

6.6.2 Shellfish

- Temperature, oxygen, pH and salinity profiles for various geographic locations in conjunction with trends and projections
- Ocean acidification research on the complete lifecycle of calcifying organisms
- MSX research, ecology, physiology and proliferation
- Spread of pathogens in relation to climate change

6.6.3 Modeling

- Smaller scale modeling in conjunction with larger scale models
- Identifying optimal culture areas for the expansion of individual or multiple species
- Identifying areas which may become sub-optimal for individual species or multiple species
- Risk modelling of pest and pathogen incidence in relation to climate change factors and the relative risk to cultured species by geographic location
- Expanding and manipulating current models as well as analyzing past and establishing real time data series of high culture zones

6.7 GENERAL KNOWLEDGE GAPS

There is a need for inshore oceanographic information, perhaps through more cost effective methods for collecting data that may need to be developed and implemented. Therefore, hydrographic profiling of high culture zones and surrounding areas need to be conducted to identify potential changes in ocean temperature, oxygen, salinity and pH. This will aid to identify whether critical levels are being approached or attained on a seasonal and annual basis (including development of an oceanographic data base and experimentation with remote sensors).

There is yet no evidence of an increase in the frequency or intensity of storms in the Atlantic basin, but any storm may be expected to be exacerbated by rising sea-levels. The impact of storms may lead to structural damage, salinity changes, an introduction of disease or predators during flood episodes, and an increase in escapees (leading to the potential for negative cultured/wild stock interactions) (Handisyde et al. 2006). As such, it would be useful to understand more about the changing oceanographic conditions.

Earlier life stages are studied more than adult stages due to ease of experiments. Therefore, experiments related to environmental stress on cultured organisms nearing harvest size (laboratory, and if possible in sea cage commercial systems for adult stages), particularly those focusing on multiple stressors (temperature and oxygen) need to be conducted to gain a better understanding of how aquaculture may be impacted by climate change.

6.8 CONCLUSION

The physiological environmental thresholds of the species being farmed in Atlantic Canada are currently within the range of the Atlantic Ocean's environmental conditions. This current situation enables the scientific and industrial sectors to identify and predict future environmental conditions in order to prepare for change in a sustainable, environmentally sound manner. Models have already been established on a smaller scale, which predict oxygen levels in and around aquaculture sites as well as studies which have been conducted to monitor oxygen and temperature (Burt et al, 2011; Chang et al, 2009; Mansour et al, 2008; Björnsson et al., 2007). These are some of the first commercial scale models and monitoring studies to be created and conducted. They are very important resources that can be utilized and referred to in order to predict and determine what will happen in various geographic locations for individual species. Real time series are important to verify these models and in some cases reveal a trend for an area that a model did not predict.

Environmental models and monitoring will be critical in the expansion and reduction of culture zones, which are already being utilized and developed for northern areas spanning to the Gulf of Maine. This is where models examining larger and small-scale localities will be important for future aquaculture endeavours. Warmer waters are expanding northwards to geographic areas that were cooler and not ideal for aquaculture. This may open up some new locations that may be ideal for culture of certain species, suppress parasitic and viral infections and vice versa in areas that are on the warmer scale within Atlantic Canada. Increasing water temperature may also prolong the growing period in northern regions but reduce them in southern regions (species specific). This increase in temperature and changes in environmental parameters and expansion of geographic culture zones will also have secondary implications associated with them such as; parasitic and viral migration and proliferation. There are still unknowns associated with parasites such as sea lice (for salmonids) and MSX (for oysters), and viruses that can be devastating to the health of the main cultured species in Atlantic Canada. Additional research should be focused on these parasites and viruses as they threaten not only cultured stocks but wild populations as well.

6.9 REFERENCES

Almada-Villela, P.C., Davenport, J., and Gruffydd, L.D. 1982. The effect of temperature on the shell growth of young *Mytilus edulis* L. Journal of Experimental Marine Biology and Ecology. 59: 275-288

Austreng, E., Storebakken, T., and Åsgård, T. 1987. Growth Rate Estimates for Cultured Atlantic Salmon and Rainbow Trout. Aquaculture, 60: 157-160

Baker, S.M., and Mann, R. 1994. Description of metamorphic phases in the oyster *Crassostrea virginica* and effects of hypoxia on metamorphosis. Mar. Ecol. Prog. Ser. 104: 91-99

Bayne, B.L. 1976. Marine mussels: their ecology and physiology. Cambridge: Cambridge University Press.

Berg, J.A., Bjerkeng, B., Pettersen, O., Schaanning, M.T., and Øxnevad, S. 2006. Effects of increased sea water concentrations of CO_2 on growth of the bivalve *Mytilus edulis* L. Chemosphere. 62: 681-687.

Billard, R., and Nadot, F. 1989. "Changemont de nom de la truite arc-en-ciel *Salmo gairdneri* (Richarsdson) en *Oncorhynchus mykiss* (Walbaum). La pisciculture française. 97: 19-20.

Björnsson, B., Steinarsson, A., and Árnason, T. 2007. Growth model for Atlantic cod (*Gadus morhua*): Effects of temperature and body weight on growth rate. Aquaculture. 271: 216-226

Björnsson, B., Steinarsson, A., and Oddgeirsson, M. 2001. Optimal temperature for growth and feed conversion of immature cod (*Gadus morhua* L.). ICES. J. Mar. Sci. 1: 29-38

Bøhle, B. 1972. Effects of adaption to reduced salinity on filtration activity and growth of mussels (*Mytilus edulis*). Journal of Experimental Marine Biology and Ecology. 10:41-49

Bolton-Warberg, M., and FitzGerald, R.D. 2012. Benchmarking growth of farmed Atlantic cod, *Gadus morhua*: a case study in Ireland. Aquaculture Research. 43: 670-678

Boxaspen, K. 2006. A review of the biology and genetics of sea lice. ICES Journal of Marine Science. 63: 1304-1316

Boxaspen, K., and Naess, T. 2000. Development of eggs and the planktonic stages of salmon lice (*Lepeophtheirus salmonis*) at low temperatures. Contributions to Zoology. 69: 51-55

Boyd, J.N., and Burnett, L.S. 1999. Reactive oxygen intermediate production by oyster hemocytes exposed to hypoxia. J. Exp Biol. 202: 3135-3143

Brenko, M.H., and Calabrese, A. 1969. The combined effects of salinity and temperature on larvae of the mussel *Mytilus edulis*. Marine Biology. 4: 224-226

Burt, K., Hamoutene, D., Mabrouk, G., Lang, C., Petstow, T., Drover, D., Losier, R., and Page, F. 2011. Environmental conditions and occurrences of hypoxia within production cages of Atlantic salmon on the South Coast of Newfoundland. Aquaculture Research DOI: 10.1111/j.1365-2109.2011.20867.x.

Calabrese, A., and Davis, H.C. 1966. The pH Tolerance of Embroys and Larvae of Mercenaria mercenaria and *Crassostrea virginica*. Biological Bulletin. 131: 427-436

Caldeira, K., and Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. Nature. 425: 365.

Canadian Aquaculture Industry Alliance. http://www.aquaculture.ca/files/species-oysters.php . Website viewed on March 15, 2012.

Canadian Aquaculture Industry Alliance. http://www.aquaculture.ca/files/species-atlantic-cod.php. Website viewed on April 18, 2012.

Carriker, M.R. 1951. Ecological Observations on the Distribution of Oyster Larvae in New Jersey Estuaries. Ecological Monographs. 21: (1) 19-38

Chabot, D., and Claireaux, G. 2008. Environmental hypoxia as a metabolic constraint on fish: The case of Atlantic cod, *Gadus morhua*. Marine Pollution Bulletin. 57: 287-294.

Chabot, D., and Dutil, J.-D. 1999. Reduced growth of Atlantic cod in non-lethal hypoxic conditions. Journal of Fish Biology. 55: 472-491

Chang, B.D., F.H. Page, R.J. Losier., and E.P. McCurdy. 2009. Characterization of dissolved oxygen concentrations in the vicinity of salmon farms in southwestern New Brunswick, Bay of Fundy. *Aquacul. Assoc. Canada Spec. Publ.No. 15:25-27*

Chapple, J.P., Smerdon, G.R., Berry, R.J., and Hawkins, A.J.S. 1998. Seasonal changes in stress-70 protein levels reflect thermal tolerance in the marine bivalve *Mytilus edulis* L. Journal of experimental Marine Biology and Ecology. 229: 53-68

Cochrane, K.; De Young, C.; Soto, D.; Bahri, T. (eds). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. *FAO Fisheries and Aquaculture Technical Paper*. No. 530. Rome, FAO. 2009. 212p.

Comeau, L.A., Pernet, F., Tremblay, R., Bates, S.S., and LeBlanc, A. 2008. Comparison of eastern oyster (*Crassostrea virginica*) and blue mussel (*Mytilus edulis*) filtration rates at low temperatures. Canadian Technical Report of Fisheries and Aquatic Sciences. 2810

Communications Branch Fisheries and Oceans Canada. 1993. Underwater World. The American Oyster. Cat No:. Fs 41-33/14-1993E. ISBN: 0-662-20550-2

Communications Branch Fisheries and Oceans Canada. 2008. Facts and Figures: Aquaculture in Canada. Cat No.: Fs1-15/2006. ISBN: 978-0-662-05850-2

Communications Branch Fisheries and Oceans Canada. 2008. Facts and Figures: Aquaculture in Canada. Cat No.: FS49-9/2011. ISBN: 978-1-100-52809-0

Coulthard, H.S. 1929. Growth of the sea mussel. Contributions to Canadian Biology and Fisheries. 4: 123-136

Delabbio, J. 1995. Arctic Charr Culture in Atlantic Canada. In "Cold-Water Aquaculture in Atlantic Canada. Second Edition". Edited by Bogden, A.D. Pg 83-106.

De Silva, S.S. and Soto, D. 2009. Climate change and aquaculture: potential impacts, adaptation and mitigation. In K. Cochrane, C. De Young, D. Soto and T. Bahri (eds). Climate change implications for fisheries and aquaculture. Overview of current scientific knowledge. *FAO Fisheries and Aquaculture Technical Paper*. No. 530. Rome. FAO. pp. 151–212.

Drinkwater, K.F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES Journal of Marine Science. 62: 1327-1337

Dubé , P., and Mason, E. 1995. Trout Culture in Atlantic Canada. Coldwater Aquaculture in Atlantic Canada. Edited by Bogden, A.D. 107-144.

Dutil, J.-D., Munro, J., Audet, C., and Besner, M. 1992. Seasonal variation in the physiological response of Atlantic cod (*Gadus morhua*) to low salinity. Can. J. Fish. Aquat. Sci. 49: 1149-1156

Elliott, J.M., and Elliott J.A. 2010. Temperature requirements of Atlantic Salmon *Salmo salar*, brown trout *Salmo trutta* and Arctic charr *Salvelinus alpinus*: predicting the effects of climate change. Journal of Fish Biology 77: 1793-1817.

Ewart, J.W. and Ford, S.E. 1993. History and Impact of MSX and Dermo Diseases on Oyster Stocks in the Northeast Region. NRAC Fact Sheet No. 200.

Fabry, V.J., Seibel, B.A., Feely, R.A., and Orr, J.C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science. 65: 414-432

Fahay, M.P., Berrien, P.L., Johnson, D.L., and Morse, W.W. 1999. Essential Fish Habitat Source Document: Atlantic Cod, *Gadus morhua*, Life History and Habitat Characteristics. NOAA Technical Memorandum NMFS-NE-124

Falk, K., Namork, E., Rimstad, E., Mjaaland, S., and Dannevig, B.H. 1997. Characterization of infectious salmon anemia virus, an orthomyxo-like virus isolated from Atlantic salmon (*Salmo salar* L.). J. Virol. 71: 9016-9023.

FAO. 2009. The state of world fisheries and aquaculture 2008. Rome, FAO: 76 pp.

Fletcher, G.L., Wroblewskii, J.S., Hickey, M.M., Blanchard, B., Kao, M.H., and Goddard, S.V. 1997. Freezing resistance of caged Atlantic cod (*Gadus morhua*) during a Newfoundland winter. Can. J. Fish. Aquat. Sci. 54: 94-98.

Forsberg, O.I. 1994. Modeling oxygen consumption rates of post-smolt Atlantic salmon in a commercial-scale, land-based farms. Aquaculture International 2: 180-196.

Forsberg, O.I., and Bergheim, A. 1996. The Impact of Constant and Fluctuating Oxygen Concentrations and Two Water Consumption Rates on Post-smolt Atlantic Salmon Prodction Parameters. Aquacultural Engineering. 15:327-347.

Frommel, A.Y., Maneja, R., Lowe, D., Malzahn, A.M., Geffen, A.J., Folkvord, A., Piatkowski, U., Reusch, T.B.H., and Clemmesen, C. 2012 Severe tissue damage in Atlantic cod larvae under increasing ocean acidification. Nature Climate Change. 2: doi: 10.1038/NCLIMATE1324

Galtsoff, P.S. 1964. The American oyster *Crassostrea virginica* Gmelin. U.S. Fish and Wildlife Service Fishery Bulletin. 64: 1-480

Garcia, H.E., and Keeling, R.F. 2002. The change in oceanic O_2 inventory associated with resent global warming. PNAS. 99: 784807853

Gazeau, F., Gattuso, J.-P., Dawber, C., Pronker, A.E., Peene, J., Heip, C.H.R., and Middelburg, J.J. 2010. Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*. Biogeoscience. 7: 2051-2060

Gilmour, K. M., and Perry, S. F. 2009. Carbonic anhydrase and acid-base regulation in fish. J. Exp. Biol. 212: 1647-1661.

Gonzalez, J.G., and Yevich, O. 1976 Responses of an estuarine population of the blue mussel *Mytilus edulis* to heated water from a steam generating plant. Marine Biology. 34:177-189

Handeland, S.O., Björnsson, B. Th., Arnesen, A.M., and Stefansson, S.O. 2003. Seawater adaption and growth of post-smolt Atlantic salmon (*Salmo salar*) of wild and farmed strains. Aquaculture, 220: 367-384

Handeland, S.O., Imsland, A.K., and Stefansson, S.O. 2008. The effect of temperature and fish size on growth, feed intake. Food conversion effiency and stomach evacuation rate of Atlantic salmon post-smolts. Aquaculture, 283: 36-42.

Handisyde, N.T., Ross, L.G., Badjeck, M-C. and Allison, E.H. 2006. The effects of climate change on world aquaculture: a global perspective. Final Technical Report, DFID Aquaculture and Fish Genetics Research Programme, Stirling Institute of Aquaculture, Stirling, U.K., 151 pp. Available at www.aqua.stir.ac.uk/GISAP/pdfs/Climate_full.pdf

Hart, D.R. and Chute, A.S. 2004. Essential Fish Habitat Source Document: Sea scallop, *Placopecten magellanicus*, life history and habitat characteristics. Second edition. NOAA Technical Memorandum NMFS-NE-189. 21 pp.

Hill, M. 1992. Trout (Marine) Aquaculture Development Planning Report. Nova Scotia Department of Fisheries Manuscript and Technical Report Series. Project Report No. 92-04

Heuch, P.A., Knutsen, J.A., Knutsen, H., Schram, T. 2002. Salinity and temperature effects on sea lice over-wintering on sea trout *(Salmo trutta)* in coastal areas of the Skagerrak. J. Mar. Biol. Assoc. UK. 82:887–892

Hofmann, E., Ford, S., Powell, E., and Klinck, J. 2001. Modelingstudies of the effect of climate variability on MSX disease in eastern oyster (*Crossostrea virginica*) populations. Hydrobiologia. 460: 195-212.

Imsland, A.K., Foss, A., Folkvord, A., Stefansson, S.O., and Jonassen, T.M. 2005. The interrelation between temperature regimes and fish size in juvenile Atlantic cod (*Gadus morhua*): effects on growth and feed conversion efficiency. Fish Physiology and Biochemistry. 31: 347-361

Incze, L.S., Lutz, R.A., and Watling, L. 1980. Relationships between effects of environmental temperature and seston on growth and mortality of *Mytilus edulis* in a temperate northern estuary. Marine Biology. 57:147-156

Jobling, M. 1994. Fish Bioenergetics. Chapman and Hall. London. Printed in Great Britain by St. Edmundsbury Press.

Johnston, G. 2002. Arctic Charr Aquaculture. Fishing News Books, a division of Blackwell Publishing.

Johnson, S.C., and Albright, L.J. 1991. The developmental stages of *Lepeophtheirus salmonis* (Krøyer, 1837)(Copepoda: Caligidae). Can. J. Zool. 69: 929-950.

Jones, S.j., Mieszkowska, N., and Wethey, D.S. 2009. Linking Thermal Tolerances and Biogeography: *Mytilus edulis* (L.) at its Southern Limit on the East Coast of the United States. Biol. Bull. 217: 73-85.

Kazakov, R.V., and Khalyapina, L.M. 1981. Oxygen consumption of adult atlantic salmon (*Salmo salar* L.) males and females in fish culture. Aquaculture, 25: 289-292.

Kiemer, M.C.B., and Black, K.D. 1997. The effects of hydrogen peroxide on the gill tissues of Atlantic salmon, *Salmo salar* L. Aquaculture. 153: 181-189.

Lambert, Y., Dutil. J.-D., and Munro, J. 1994. Effects of Intermediate and Low Salinity Conditions on Growth Rate and Food Conversion of Atlantic Cod (*Gadus morhua*). Can. J. Fish. Aquat. Sci. 51: 1596-1576.

Loder, J.W., J. Chassé, P. Galbraith, G. Han, D. Lavoie and others. 2013. Summary of climate change trends and projections for the Atlantic Large Aquatic Basin off Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3051 (under revision)

Lovoie, R.E. 1995. Culture of the American Oyster, *Crassostrea virginica*. In "Cold-Water Aquaculture in Atlantic Canada. Second Edition". Edited by Bogden, A.D. Pg 189-224.

Loosanoff, V.L. 1952. Behavior of oysters in water of low salinity. Proc. Natl. Shellfish. Assoc. 135-151.

Loosanoff, V.L. 1958. Some aspects of behavior of oysters at different temperatures. Biol. Bull: 114, 57-70.

MacInnes, J.R., and Calabrese, A. 1979. Combined Effects of Salinity, Temperature, and Copper on the Embryos and Early Larvae of the American Oyster, *Crassostrea virginica*.

MacLeod, M.G. 1977. Effects of Salinity of Food Intake, Absorption and conversion in the Rainbow Trout *Salmo gairdneri*. Marine Biology. 43: 93-102.`

Mallet, A.L., Carver, C.E.A., and Freeman, K.R. 1990. Summer mortality of the blue mussel in eastern Canada: spatial, temporal, stock and age variation. Marine Ecology Progress Series. 67:35-41

Mallet, A., and Myrand. 1995. Salmon Aquaculture: Present Status and Prospects for the Future. In "Cold-Water Aquaculture in Atlantic Canada. Second Edition". Edited by Bogden, A.D. Pg 35-81.

Mansour, A., Hamoutene, D., Mabrouk, G., Puestow, T., and Barlow, E. 2008. Evaluation of some environmental parameters for salmon aquaculture cage sites in Fortune Bay, Newfoundland : emphasis on the occurrence of hypoxic conditions. Canadian Technical Report of Fisheries and Aquatic Sciences, 2814,21pp.

Martin, J.L., LeGresley, M.M., and Richard, D.J.A. 1998. Toxic Phytoplankton, PSP and ASP toxicity data during the years1988-1996 from the southwest Bay of Fundy, Eastern Canada. *In* B. Reguera, J. Blance, Ma L. Fernández, and T. Wyatt (Eds.) Harmful Algae. Xunta de Galicia and Intergovernmental Oceanographic Commission of UNESCO 1998. pp 233-234.

Martin, J.L., Legresley, M.M., and Page, F.H. 2001. Aquaculture and Phytoplankton Blooms in the Southwest Bay of Fundy. Aquaculture Association of Canada. Special Publication No. 4. 103-106.

McKenzie, R. A. 1934. Cod and water temperature. Biological Board of Canada, Atlantic Progress Report. 12: 3-6

McKenzie, R. A. 1938. Cod take smaller bites in ice-cold water. Fisheries Research Board of Canada, Atlantic Progress Report. 22: 12-14

Mortensen, S.H., Nilsen, R.K., and Hjeltnes, B. 1998. Stability of an infectious pancreatic necrosis virus (IPNV) isolate stored under different laboratory conditions. Diseases of Aquatic Organisms. 33: 67-71.

Mustafa, A., Conboy, G.A., and Burka, J.F. 2000. Lifespan and reproductive capacity of sea lice, *Lepeophtheirus salmonis*, under laboratory conditions. Aquaculture Association of Canada, Special Publication. 4: 113-114

Newell, R.I.E., 1989. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (North and Mid-Atlantic) – blue mussel. U.S. Fish. Wildl. Serv. Biol. Rep. 82(11. 102). U.S. army Corps of Engineers, TR E1-82-4. 25pp.

Odense, P., Bordeleau, A., and Guilbault, R. 1966. Tolerance levels of cod (*Gadus morhua*) to low salinity. J. Fish. Res. Board Can. 23: 1465-1467.

Ono, T., Rios, A.F. 2004. The oceanic sink for anthropogenic CO_2. Science 305 (5682), 367-371.

Pauley, G.B., Bortz, B.M., and Shepard, M.F. 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)-Steelhead trout. U.S. Fish. Wildl. Serv. Biol. Rep. 82(11.62)

Pedersen, T., and Jobling, M. 1989. Growth Rates of Large, Sexually Mature Cod, *Gadus morhua*, in Relation to Condition and Temperature During an Annual Cycle. Aquaculture. 81: 161-168

Pennell, W., and Barton, B.A. 1996. Principles of Salmon Culture. Developments in Aquaculture and Fisheries Science. Vol 29.

Pernet, F., Tremblay, R., Comeau, L., and Guderley, H. 2007. Temperature adaption in two bivalve species from different thermal habitats: energetics and remodeling of membrane lipids. The Journal of Experimental Biology. doi: 10.1242/jeb.006007

Perry, S. F., and Gilmour, K. M. 2006. Acid-base balance and CO_2 excretion in fish: Unanswered questions and emerging models. Respir. Physiol. Neurobiol. 154: 199-215.

Plante, S., Chabot. D., and Dutil, J.-D. 1998. Hypoxia tolerance in Atlantic cod. Journal of Fish Biology. 53: 1342-1356

Rask, M. 1984. The effect of low pH on perch, Perca fluviatilis L. II. The Eeffect of acid stress on different development stages of perch. Ann. Zool. Fennici. 21: 9-13

Riebesell, U., Zondervan, I., Rost, B., Tortell, P., Zeebe, R.E., and Morel, F.M.M. 2000. reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature. 407: 364-367

Rikardsen, A.H. 2004. Seasonal occurrence of sea lice *Lepeophtheirus salmonis* on sea trout in two north Norwegian fjords. J. Fish. Biol. 65:711–722

Robinson, G.D., Dunson, W.A., Wright, J.E., and Mamolito, G.E. 1976. Differences in low pH tolerance among strains of brook trout (*Salvelinus fontinalis*). J. Fish Biol. 8: 5-17.

Robinson, S.M.C., Martin, J.D., Page, F.H., and Losier, R. 1996. Temperature and Salinity Characteristics of Passamaquoddy Bay and Approaches Between 1990 and 1995. Canadian Technical Report of Fisheries and Aquatic Sciences. No. 2139

Royal Society, 2005. Oce3an acidification due to increasing atmospheric carbon dioxide. Policy Document 12/05. The Royal Society, London. 60

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.H., Kozyr, A.,

Saunders, R.L. 1987. Winterkill! The reality of lethal winter sea temperatures in east coast salmon farming. Aquaculture Association of Canada Bulletin, 1: 36-37.

Saunders, R.L., Muise, B.C., and Henderson, E.B. 1975. Mortality of salmonids cultures at low temperature in sea water. Aquaculture, 5: 243-252

Saunders, R.L. 1995. Salmon Aquaculture: Present Status and Prospects for the Future. In "Cold-Water Aquaculture in Atlantic Canada. Second Edition". Edited by Bogden, A.D. Pg 255-296.

Schurmann, H., and Steffensen, J.F. 1992. Lethal oxygen levels at different temperatures and the preferred temperature during hypoxia of the Atlantic cod, *Gadus morhua* L. Journal of Fish Biology. 41: 927-934.

Sedgwick, S.D. 1973. Trout Farming Handbook. Seeley, Service and Co London. Pg 103-117

Sherman, R.K., and Lentz, S.J. 2010. Long-Term Sea Surface Temperature Variability along the U.S. East Coast. Journal of Physical Oceanography. 40: 1004-1017

Shumway, S.A. 1996. Natural environmental factors. In The Eastern Oyster *Crassostrea virginica* (ed. V.S. Kennedy, C.R. Newell and A.F. Eble), pp. 467-513. College Park, MA: Maryland Sea Grant Book.

Shumway, S.E. and Koehn, R.K. 1982. Oxygen Consumption in the American Oyster *Crassostrea virginica*. Mar. Ecol. Prog. Ser. 9: 59-68

Statistics Canada. 2011. Aquaculture Statistics 2010. Catalogue no. 23-222-x. Referenced April, 2012

Studies on the comparative utilization of oxygen by living and dead oysters. Proc. Natl. Shellfsh. Assoc. 48: 92-102.

Stephenson M.F., McGladdery, S.E., Maillet, M., and Veniot, A. 2003. First reported occurrence of MSX in Canada. Journal of Shellfish Research 22: 355 (Abstract).

Stewart, P.L. 1994. Environmental Requirements of the Blue Mussel (*Mytilus edulis*) in Eastern Canada and its Response to Human Impacts. Canadian Technical Report of Fisheries and Aquatic Sciences 2004.

Stien, A., Bjørn, P.A., Heuch, A.H., and Elston, D.A. 2005. Popultion dynamics of salmon lice *Lepeophtheirus salmonis* on Atlantic salmon and sea trout. Marine Ecology Progress Series. 290: 263-275

Sutterlin, A.M. and Stevens, E.D. 1992. Thermal behaviour of rainbow trout and Arctic char in cages moored in stratified water. Aquaculture. 102: 65-75

Teskeredžić, E., Teskeredžić, A., Tomec, M., and Modrusan, Z. 1989. A Comparison of the Growth Performance of Rainbow Trout (*Salmo gairdneri*) in Fresh and Brackish Water in Yugoslavia. Aquaculture. 77: 1-10

Thomassen, J.M. 1993. Hydrogen peroxide as a delousing agent for Atlantic salmon. In: Boxhall, G.A., Dwfaye, D. (Eds.), Pathogens of Wild and Farmed Fish. Sea Lice. Ellis Horwood Limited.

Thorarensen, H., and Farrell, A.P. 2011. The biological requirements for post-smolt Atlantic salmon in closed-containment systems. Aquaculture 312: 1-14

Wells, H.W., and Gray, I.E., 1960. The seasonal occurrences of *Mytilus edulis* on the Carolina coast as a result of transport around Cape Hatteras. Biol. Bull. (Woods Hole) 119: 550-559.

Wildish, D.J., Keizer, O.D., Wilson. A.J., and Martin, J.L. 1993. Seasonal changes of dissolved oxygen and plant nutrients in seawater near salmonid net pens in the macrotidal Bay of Fundy. Can. J. Fish. Aquat. Sci. 50: 303-311.

World Organization for Animal Health. 2009. Infectious haematopoietic anaemia. Manual of Diagnostic Tests for Aquatic Animals 2011. Chapter 2.3.4. http://www.oie.int/international-standard-setting/aquatic-manual/access-online/

APPENDIX 6.1: MAPS OF AQUACULTURE SITES IN ATLANTIC CANADA AND QUEBEC

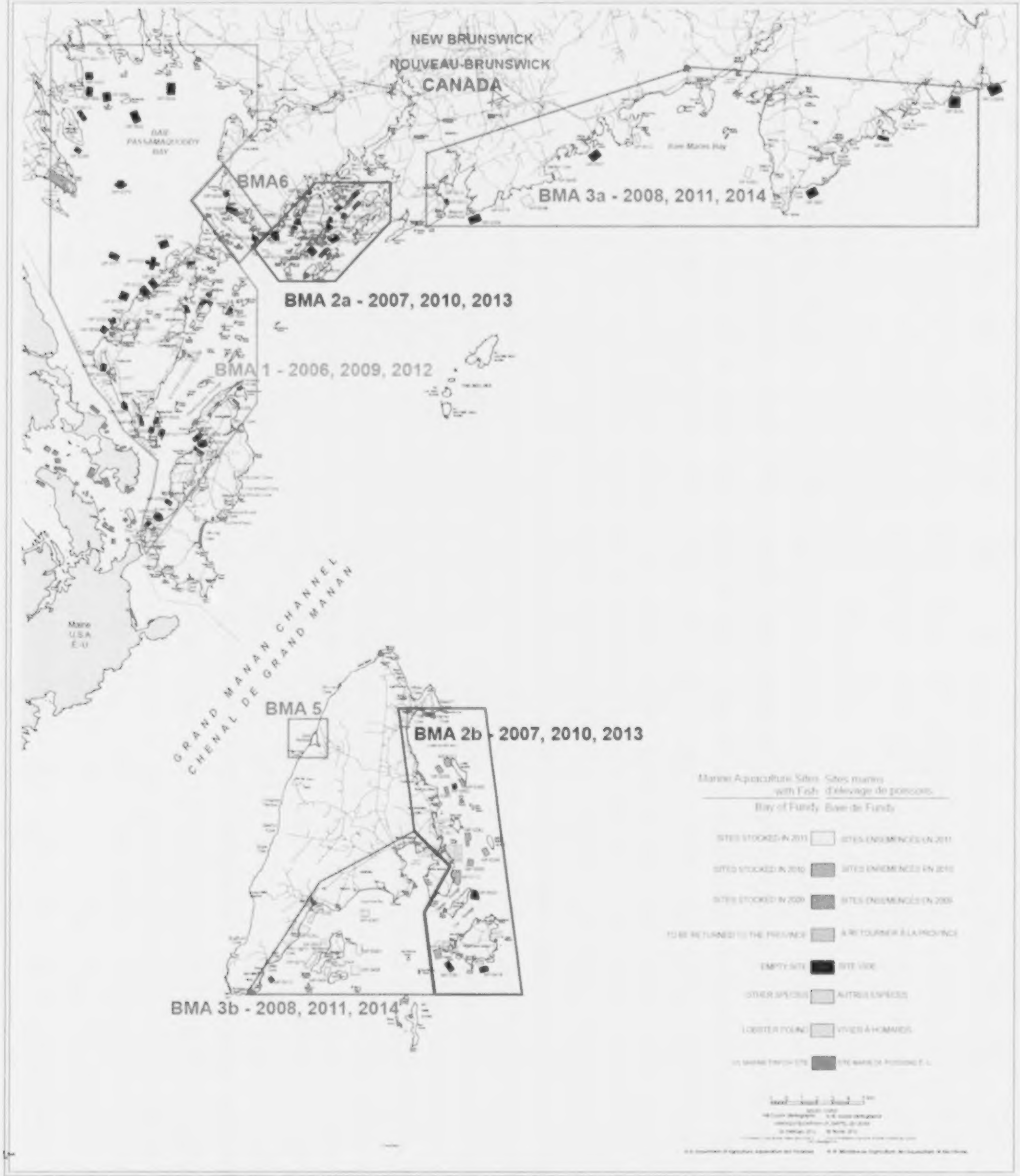
NEW BRUNSWICK
NOUVEAU-BRUNSWICK
CANADA
BAIE PASSAMAQUODDY BAY
BMA6
BMA 3a - 2008, 2011, 2014
BMA 2a - 2007, 2010, 2013
BMA 1 - 2006, 2009, 2012
Maine U.S.A. E.-U.
GRAND MANAN CHANNEL
CHENAL DE GRAND MANAN
BMA 5
BMA 2b - 2007, 2010, 2013
BMA 3b - 2008, 2011, 2014
Marine Aquaculture Sites with Fish
Sites marins d'élevage de poissons
Bay of Fundy
Baie de Fundy
SITES STOCKED IN 2011
SITES ENSEMENCÉS EN 2011
SITES STOCKED IN 2010
SITES ENSEMENCÉS EN 2010
SITES STOCKED IN 2009
SITES ENSEMENCÉS EN 2009
TO BE RETURNED TO THE PROVINCE
À RETOURNER À LA PROVINCE
EMPTY SITE
SITE VIDE
OTHER SPECIES
AUTRES ESPÈCES
LOBSTER POUND
VIVIERS À HOMARDS

Figure 6–1 Bay Management Areas, Salmon Aquaculture Sites and Other Species Sites in the Bay of Fundy. (Map Provided by Province of New Brunswicks Department of Agriculture, Aquaculture and Fisheries)

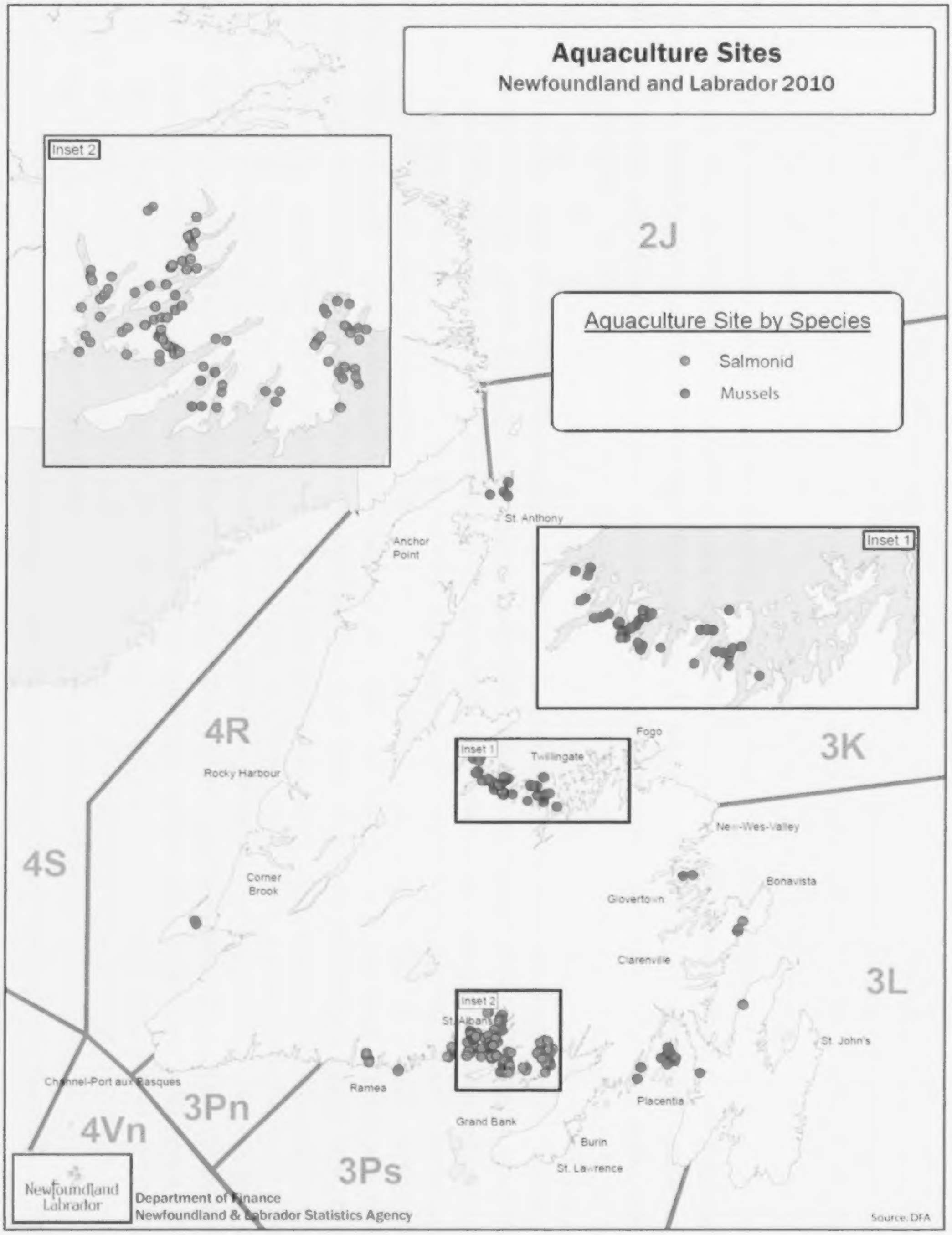
Aquaculture Sites
Newfoundland and Labrador 2010
Inset 2
2J
Aquaculture Site by Species
● Salmonid
● Mussels
St. Anthony
Anchor Point
Inset 1
4R
Rocky Harbour
Fogo
Twillingate
3K
New-Wes-Valley
4S
Corner Brook
Bonavista
Glovertown
Clarenville
3L
Inset 2
St. Albans
St. John's
Channel-Port aux Basques
Ramea
Placentia
3Pn
Grand Bank
4Vn
Burin
St. Lawrence
3Ps
Newfoundland Labrador
Department of Finance
Newfoundland & Labrador Statistics Agency
Source: DFA

Figure 6–2 Salmonid and Mussel Aquaculture Sites in Newfoundland and Labrador 2010. (Map Provided by Newfoundland and Labradors Department of Fisheries and Aquaculture)

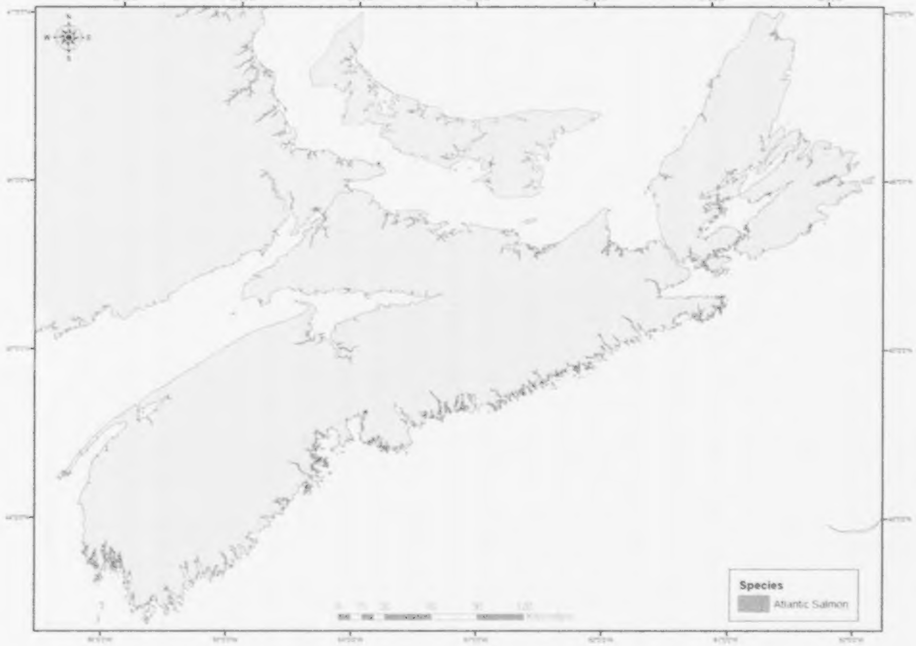
Species
Atlantic Salmon

Figure 6–3 Nova Scotia's Atlantic Salmon Aquaculture Areas. (Map Provided by Nova Scotia Department of Fisheries and Aquaculture)

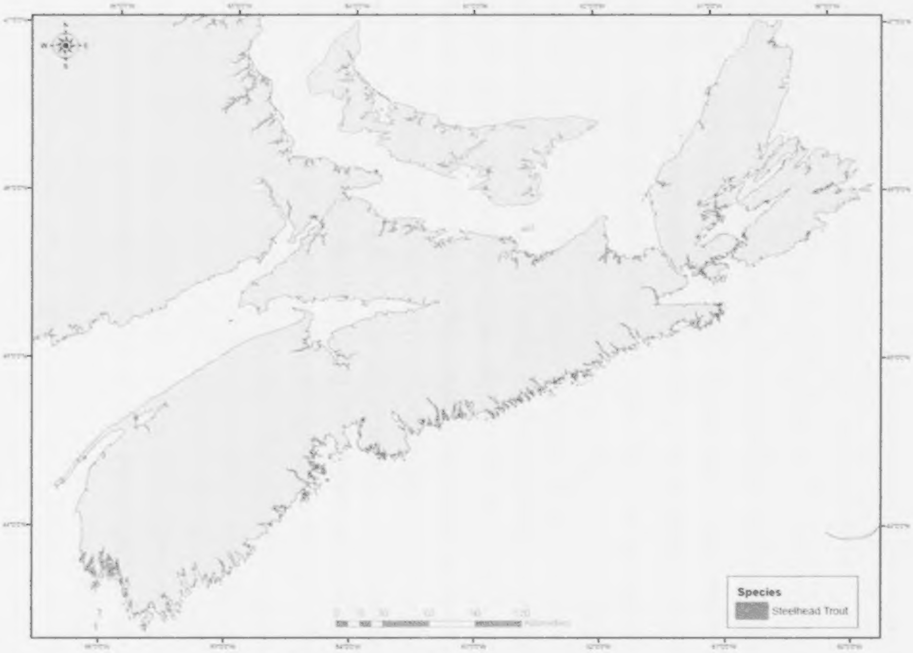
Species
Steelhead Trout

Figure 6–4 Nova Scotia's Steelhead Trout Aquaculture Areas. (Map Provided by Nova Scotia Department of Fisheries and Aquaculture)

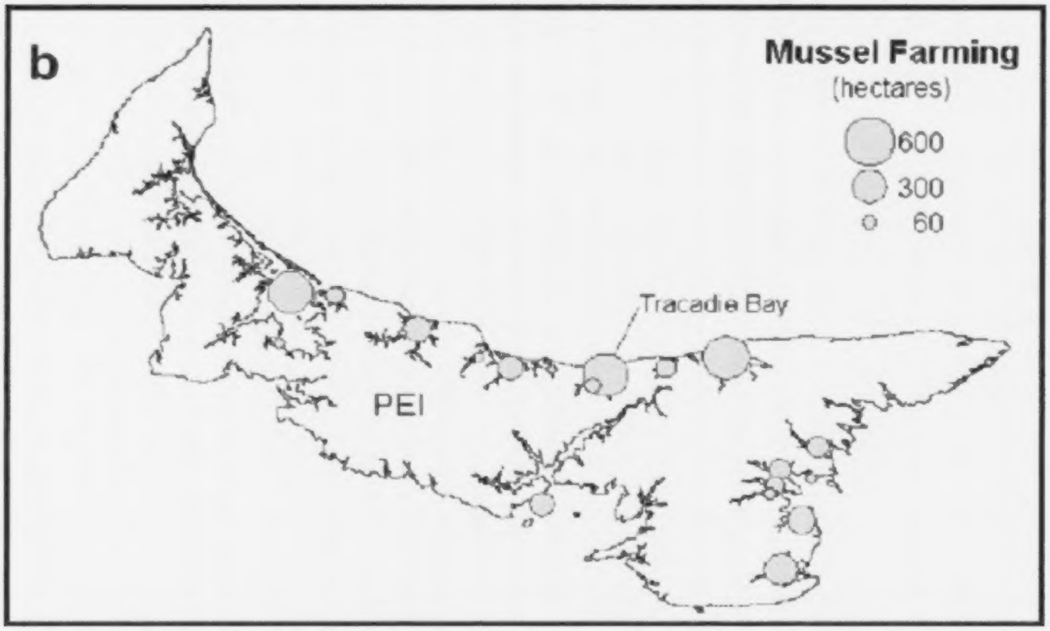
b
Mussel Farming
(hectares)
600
300
60
Tracadie Bay
PEI

Figure 6–5 Mussel farms in PEI (Comeau et al. 2008).

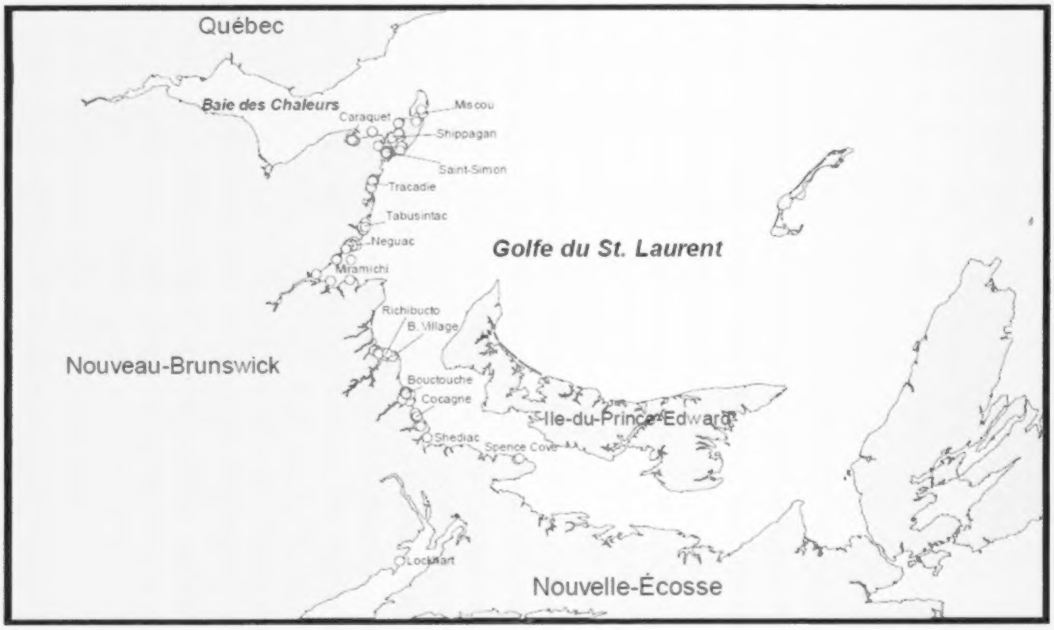
Québec
Baie des Chaleurs
Caraquet
Miscou
Shippagan
Saint-Simon
Tracadie
Tabusintac
Neguac
Miramichi
Golfe du St. Laurent
Richibucto
B. Village
Nouveau-Brunswick
Bouctouche
Cocagne
Ile-du-Prince-Edward
Shediac
Spence Cove
Lockhart
Nouvelle-Écosse

Figure 6–6 Distribution of oyster sites in northern New Brunswick in 2005. This map can act as a reference for area where majority of current culture takes place (Comeau et al. 2006).

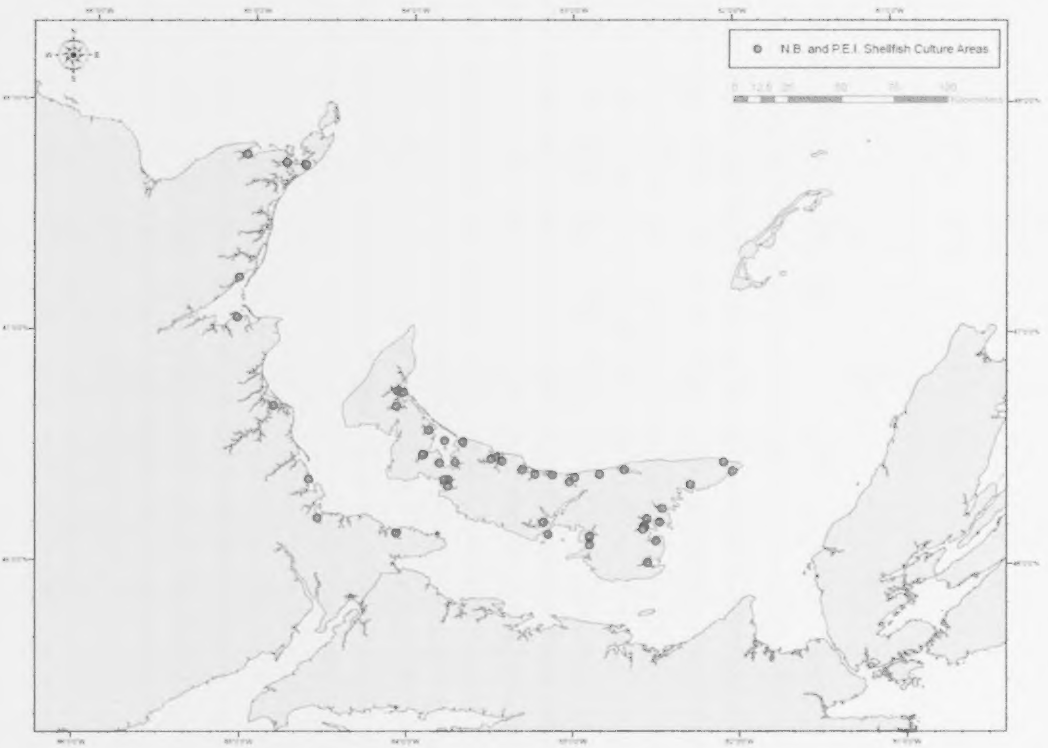
N.B. and P.E.I. Shellfish Culture Areas
Kilometers

Figure 6–7 Northern New Brunswick and PEI shellfish aquaculture sites. (Map Provided by Luc Comeau. Fisheries and Oceans Canada)

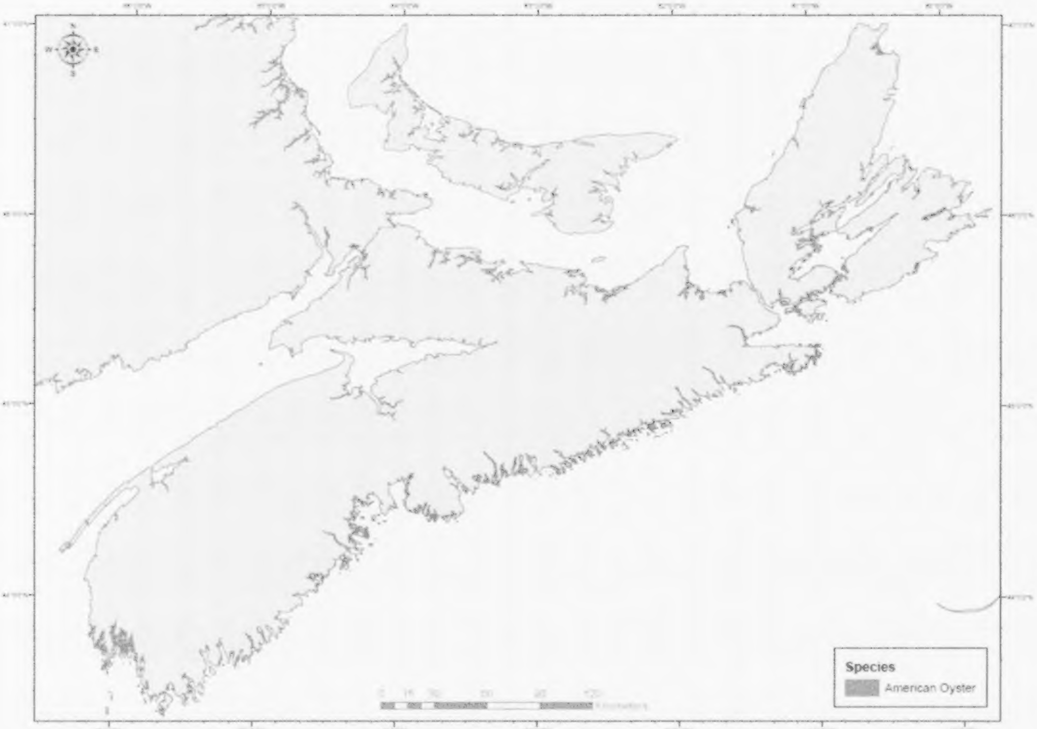
Species
▨ American Oyster
0 15 30 60 90 120
Kilometers

Figure 6–8 Nova Scotia's Blue Mussel Aquaculture Areas. (Map Provided Nova Scotia Department of Fisheries and Aquaculture)

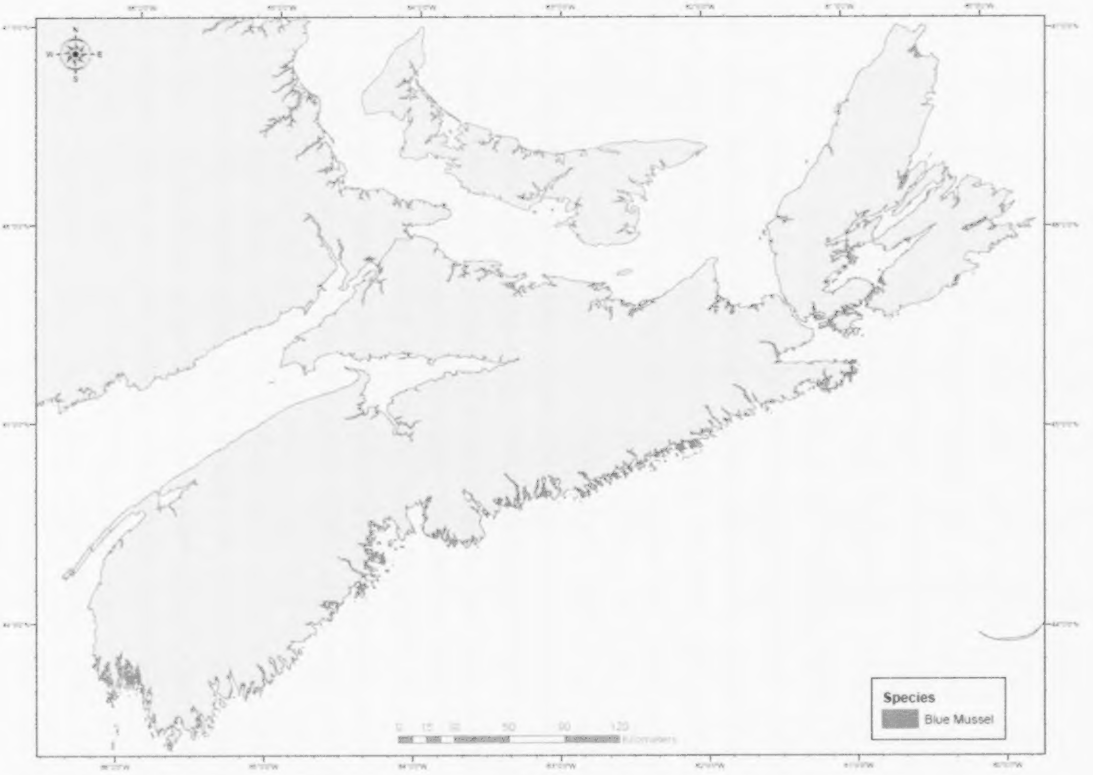
N
W
E
S
0 15 30 60 90 120
Kilometers
Species
Blue Mussel

Figure 6–9 Nova Scotia's American Oyster Aquaculture Areas. (Map Provided by Nova Scotia Department of Fisheries and Aquaculture)

APPENDIX 6.2: ENVIRONMENTAL THRESHOLDS FOR KEY CULTURED SPECIES IN ATLANTIC CANADA AND QUEBEC

Table 6–3 Atlantic Salmon (*Salmo salar*).

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Smolt +	Optimal Growth Concentration	> 8 mg/L	Optimal concentration for growth. Below this levels starts to affect performance.	Thorarnsen and Farrell 2011 Forsberg and Bergheim 1996	Literature Review Lab
Smolt +	Hypoxia	< 6 mg/L	DO where fish makes a physiological adjustment to maintain oxygen levels to tissues.	Mansour et al. 2008 Chang et al. 2009 Burt et al. 2011	Field Field Field
Adult 1.6-10 kg	Critical Oxygen Concentration	2.0-2.5 mg/L	Fish become excited and try to surface for air.	Kazakov and Khalyapina 1981	Lab
Adult 1.6-10 kg	Lethal Oxygen Concentration	1.5-1.7 mg/L	Fish asphyxiate resulting in mortality	Kazakov and Khalyapina 1981	Lab
Smolt +	Optimal Growth Range	8-12 °C	Based on growers observations in NS and NB	Saunders 1995	Book (Review)
70-150g	Optimal Growth Range	12.8 ± 0.2 °C	Optimal Growth Range 70-150g fish	Handeland et al. 2003, 2008	Lab
170-300g	Optimal Growth Range	14.0 ± 0.4 °C	Optimal Growth Range 170-300g fish	Handeland et al. 2003, 2008	Lab
Smolt +	Optimal Growth Range	14 °C	Optimal Growth Temperature for Smolt +	Handeland et al. 2003, 2008	Lab
Smolt +	Appetite Reduction	> 18 °C < 6 °C	Minimal feeding. Unfavourable for growth.	Handeland et al. 2003, 2008	Lab

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Smolt +	Stop Feeding	≤ 1 °C	No growth	Saunders et al. 1975 Handeland et al. 2003, 2008	Lab Lab
Smolt +	Upper Critical Temperature Survival Range	22-28 °C	50% of the fish can tolerate these temperatures for approximately 7 days	Elliott and Elliott 2010	Literature Review
Smolt +	Upper Lethal Temperature Limit	30-33 °C	Fish can only tolerate these temperatures for 10 minutes	Elliott and Elliott 2010	Literature Review
Smolt +	Lower Lethal Temperature Limit	-0.7 °C	Blood and tissue begin to freeze	Saunders et al. 1975 Saunders 1987	Lab Bulletin

Table 6–4 Steelhead Trout (*Oncorhynchus mykiss*).

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Smolt +	Temperature range	0-23.9 °C	Range for survival in Atlantic waters.	Pennell and Barton 1996	Book (Review)
Post Smolt	Optimal Temperature	16 °C	Optimal Temperature Post Smolt	Pennell and Barton 1996 Hill, 1992	Book (Review) Tech Report
Adults (≈ 4kg)	Optimal Temp	10-22 °C	Tends to be lower than post smolts	Pennell and Barton 1996 Hill 1992	Book (Review) Tech Report
Smolts+	Lower Lethal Limit	-0.7 °C	Blood and tissue begin to freeze	Saunders et al. 1975	Lab (Outdoor holding tank. Tidepool)
Smolts+	Upper Lethal Temperature Limit	23.9 °C	At temperature above 23.9 °C lead to stress and mortlaity	Pennell and Barton 1996	Book (Review)
Smolts+	Lower Oxygen Threshold	6-6.5 mg/L	Below this level fish become stressed leading to mortality	Dube and Mason 1995 Pennell and Barton 1996 Mansour et al. 2008 Chang et al. 2009 Burt et al. 2011	Book (Review) Book (Review) Field Field Field
Smolts+	Optimal Oxygen	≥ 8 mg/L	Optimal oxygen for all salmonids	Forsberg and Bergheim 1996 Pennell and Barton 1996 Thorarensen and Farrell 2011	Lab Book (Review) Literature Review
Smolts+	Salinity	18-33 ppt	Anadromous species so is not that critical	Macleod 1977 Pennell and Barton 1996	Lab Book (Review)
Smolts +	pH	6.5-8.0	Optimal range for growth and survival.	Pennell and Barton 1996	Book (Review)

Table 6–5 Arctic Charr (*Salvelinus alpinus*).

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Smolt +	Temp Range	0-23 °C	Survive in this temperature range	Johnston 2002	Book (Culture)
Smolt +	Optimal Growth Temp	6 °C – 15 °C	Optimal temperature range for growth	Johnston 2002	Book (Culture)
Smolt +	Upper Limit for Growth	21.5 °C	Stop feeding and growing at this temperature	Johnston 2002	Book (Culture)
Smolt +	Upper Lethal Temp Limit	> 23 °C	Become severely stressed resulting in mortality above this temperature	Johnston 2002	Book (Culture)
Smolt +	Lower Limit for Growth	0-0.3 °C	Stop growing at 0.3 °C and stop feeding at 0 °C	Johnston 2002	Book (Culture)
Smolt +	Lower Lethal Temp Limit	< 0 °C	Death occurs below this limit	Johnston 2002	Book (Culture)
Smolt +	Optimal oxygen saturation	≥ 6.5 mg/L	For ideal growth and survival, which is similar to other salmonids	Johnston 2002	Book (Culture)
Smolt +	Lower Oxygen saturation limits	65-70%	Experience a reduced efficiency in oxygen transfer	Johnston 2002	Book (Culture)
Smolt +	Lower Lethal Oxygen Limit	5 mg/L	Can tolerate this level , anything lower results in mortality	Johnston 2002	Book (Culture)
Smolt +	ph Range	5-9	Can tolerate this range	Jobling 1994	Book (Nutrition)
Smolt +	Optimal pH	6.5-8.5	Max productivity range	Jobling 1994	Book (Nutrition)
Smolt +	Lethal ph	< 4 and > 11	Lethal limits	Johnston 2002	Book (Culture)
Smolt +	Salinity Range	0-35 ppt	Can survive within this salinity range. Cannot tolerate full saline water year round.	Johnston 2002	Book (Culture)
Smolt +	Optimal Survival Range	10-35 ppt	Optimal range for survival within total range.	Johnston 2002	Book (Culture)
Smolt +	Optimal Growth	< 15 ppt	Produces the highest growth	Johnston 2002	Book (Culture)

Table 6–6 Atlantic cod (*Gadus morhua*).

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Juvenile +	Temp Range	-1.7 – 20 °C	Can survive in this temp range. Mainly found in 0-12 °C	Fletcher et al. 1997 Fahay et al. 1999 Drinkwater 2005	Field Technical Report Literature Review/ Report
Juvenile (5-800 g)	Optimal Temp Range	11-15 °C	Optimal temp range for growth	Björnsson et al. 2001 Schurmann and Steffensen 1992 Imsland et al. 2005 Pedersen and Jobling 1989	Lab Lab Lab/Field Field
1-2 year olds (800 g +)	Optimal Temp Range	7-12 °C	Optimal temp range for growth	Björnsson et al. 2001 Schurmann and Steffensen 1992 Imsland et al. 2005 Pedersen and Jobling 1989	Lab Lab Lab/Field Field
Juvenile +	Salinity Range	3-33 ppt	Cod can survive within this salinity range	Dutil et al. 1992	Lab
Juvenile +	Lethal Salinity Level	< 3 ppt	Mortality occurs at this level	Odense et al. 1966	Lab
Juvenile +	Optimal salinity	7-14 ppt	Growth was higher within this range compared to 28 ppt.	Lambert et al. 1994	Lab
Juvenile +	Optimal Oxygen	> 73% saturation	Growth begins to be affected below this level	Chabot and Dutil 1999	Lab
Juvenile +	Lethal Limit	9% 21-28%	LC_{50} for a 3-hour exposure at 2-6 °C LC_{50} for 96-hour exposure at 2-6 °C	Plante et al. 1998 Plante et al. 1998	Lab Lab

Table 6–7 Blue Mussels (*Mytilus edulis*).

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Larvae/ Juveniles	Salinity Range at 5-20 °C	15-40 ppt	Survival of larvae in salinities from 15 to 40‰ is uniformly good (70% or better).	Brenko and Lalabrese 1969	Lab
		20-25 ppt	Normal development	Bayne 1976	Book (Review)
Larvae/ Juveniles	Salinity Range at 25 °C	20-40 ppt	Survival is reduced drastically at 25 °C particularly in high (40‰) and low (20‰) salinities.	Brenko and Lalabrese 1969	Lab
Larvae/ Juveniles	Rapid Growth temperature at salinities 25-35 ppt	15 °C	Growth of larvae is most rapid at a temperature of 15 °C in salinities from 25 to 35‰	Brenko and Lalabrese 1969	Lab
	20-35 ppt	20 °C	and at 20 °C in salinities ranging from 20 to 35‰		
Larvae/ Juveniles	Optimum Temperature for Growth in salinity range 25-30 ppt	20 °C	Optimum for larval growth	Brenko and Lalabrese 1969	Lab
				Bayne 1976	Book (Review)
Larvae/ Juveniles	Lower and Upper Critical Temperature Ranges for Growth	< 10 °C	Growth decreases both at 25 °C	Brenko and Lalabrese 1969	Lab
		> 25 °C	and I0 °C and the decline is most drastic at high (40‰) and low (20‰) salinities	Bayne 1976	Book (Review)
Larvae/ Juveniles 1.5cm	Temperature Range	3-25 °C (All temps compared to growth at 10 °C)	3-5 °C growth constant but low. 15-20 °C high growth > 20 °C growth declines sharply growth ≥ 25 °C depressed.	Almada-Villela et al. 1982 Coulthard 1929 Gonzalez and Yevich 1976	Lab Lab Lab/Field
Larvae/ Juveniles	Lethal temperature limit	27 °C	Mussels cannot tolerate temperatures > 27 °C	Gonzalez and Yevich 1976	Lab/Field

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Adult	Salinity Range for survival	0-31 ppt	Can tolerate salinities in these ranges. Studies vary.	Bogden 1995	Book (Review)
		5-35 ppt		Stewart 1994	Technical Report
				Bayne 1976	Book (Review)
Adult	Salinity Range for survival	15 ppt	Minimum salinity of 15 ppt for prolonged exposure. Growth is very low.	Stewart 1994	Technical Report
				Bøhle 1972	Lab
Adult	Optimum Salinity for growth	13 ppt	Growth is severely reduced below 13 ppt	Bogden 1995	Book (Review)
		≥ 18 ppt	Acceptable growth rates ≥ 18 ppt	Bogden 1995	Book (Review)
		26 ppt	Optimum growth at 26 ppt	Bogden 1995	Book (Review)
Adult	Temperature Range	-1.5 -25 °C	≥ 20 °C should be avoided as is associated with lower growth rates and incidence of summer mortality	Bogden 1995	Book (Review)
				Newell, R.I.E 1989	Technical Report
				Coulthard 1929	Lab
			Minimal feeding at temperatures > 25 °C	Gonzalez and Yevich 1976	Lab/Field
Adult	Temperature Lethal Limit	25 °C-27 °C	Depending on area.	Stewart, 1994	Technical Report
				Brenko and Lalabrese 1969	Lab
				Newell, R.I.E 1989	Technical Report
				Bayne 1976	Book Review

Table 6–8 American Oyster (*Crassostrea virginica*).

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Adult	Temp Range	-2 – 36 °C	Survival	Galtsoff 1964 Shumway 1996	Technical Report Book (Biology)
Adult	Optimal temp range	10-20 °C	Optimal range for growth	Loosnaoff 1958 Shumway 1996 Pernet et al. 2007	Lab Book (Biology) Lab
Adult	Extreme Temp	49 °C	At low tide can withstand 49 °C for short duration	Galtsoff 1964 Shumway 1996	Technical Report Book (Biology)
Adult	Low Temp	4 °C	Stop feeding below 4 °C	Comeau et al. 2008 Pernet et al. 2007	Lab Lab
Adult	Low temp	0 °C	Are quiescent at ≤ 0 °C	Loosnaoff 1958 Pernet et al. 2007	Lab Lab
Embryos	Optimal Range	20-30 °C	Optimal range for development	MacInnes and Calabrese 1979	Lab
Adult	Salinity Range	0-40 ppt	Salinity found throughout geographic distribution	Galtsoff 1964	Technical Report
Adult	Optimal Salinity	12-28 ppt	The optimal range for growth	Loosanoff 1953 Shumway 1996	Lab Book (Biology)
Embryos	Salinity Range	3-31 ppt	Range embryos can tolerate and survive in	Carriker 1951	Field
Embryos	Optimal for development	16-30 ppt	Optimal range for development	MacInnes and Calabrese 1979	Lab
Larvae/ Spat	Optimal for development	15-22.5 ppt	Optimal range for recently set spat	Shumway 1996	Book (Biology)
Adult	Oxygen lower limit	1.0 mg/L	Can survive for 5 days in water containing 1.0 mg/L	Sparks et al. 1958	Lab

Size	Criteria	Value	Comments	Source	Type of Study/ Source
Adults	pH	7.8-8.2	Majority of spawning occurs in this pH range	Calabrese and Davis 1966	Lab
Embryos	pH	6.75-8.75	Normal embryonic development	Calabrese and Davis 1966	Lab
Larvae/ Spat	pH lower lethal limit	6.0	Lower lethal limit for larvae	Calabrese and Davis 1966	Lab
Larvae/ Spat	Optimal pH for growth	8.25-8.50	Optimal range for growth which drops rapidly at ≤ 6.75	Calabrese and Davis 1966 Shumway 1996	Lab Book (Biology)

Chapter 7 Invasive species and climate change in Atlantic Canada

A. Locke*

Gulf Fisheries Centre, Fisheries and Oceans Canada, 343 Université Avenue, P. O. Box 5030, Moncton, NB E1C 9B6

*Correspondence: Nancy.Shackell@dfo-mpo.gc.ca

Suggested Citation:

Locke, A. 2013. Invasive species and climate change in Atlantic Canada. Ch. 7 (p. 241–255) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

7.1 SUMMARY

Invasive species and climate change each pose threats to biodiversity and other ecosystem properties, and their effects are not independent. An increase in the number of introduced (all non-indigenous) and invasive (harmful non-indigenous) species in marine waters of Atlantic Canada is expected to accompany predicted climate change. Since most species already introduced to Atlantic Canada originate from warmer ecosystems and, in general, many species worldwide that are currently utilizing anthropogenic vectors to reach new range, are adapted to a broad range of environmental conditions, warming may be more likely to favour introduced than native species. A rise in temperature could lead to novel non-indigenous species expanding their ranges into Atlantic Canada from southern origins as well as already-introduced species expanding their ranges within Atlantic Canada. In addition, some existing, apparently benign, introduced species may become invasive. Coastal and estuarine waters are the most vulnerable sites of introduction, especially in man-made features, such as ports, marinas and aquaculture facilities. It is likely that climate change will increase the costs of invasive species in Atlantic Canada, or at least, sustain current levels of costs. While costs are more commonly reported, some species may provide benefits: for example, if they support fisheries or contribute to ecosystem productivity.

7.2 INTRODUCTION

Invasive species and climate change are two of the top five threats to biodiversity, along with habitat change, overexploitation, and pollution (Millenium Ecosystem Assessment 2005). Climate change and invasive species have often been treated as independent issues, but the role of climate change in exacerbating invasive species issues worldwide is now recognized (e.g., Pederson et al. 2011). Changes in climate in conjunction with societal responses to climate change are likely to alter both the number of introduced species and the impacts of invasive species. The distinction between introduced and invasive species relates to their effects. A non-indigenous species which is intentionally or accidentally transported by humans into a novel environment is an *introduced* species. The subset of introduced species causing harm to the economy, environment, human health, recreation or public welfare is termed *invasive* (CCFAM 2004).

Climate change may affect the probability that a non-indigenous species will be successfully introduced, as well as the probability that it will become invasive in its new environment. Environmental suitability is a strong determinant of the success of an introduction (Williamson et al. 1986; Blackburn and Duncan 2001). The consequences of an introduction, i.e., whether the introduced species becomes invasive, may also be influenced by climate. The impact of an introduced species may be expressed as the product of three terms that reflect its invasiveness: the spatial extent of its occupied range, its mean abundance within the range, and its per-capita or per-biomass impact on components of the ecosystem (Parker et al. 1999). Each of these three terms could be altered by climate change. The magnitude of the impact on a given native species depends not only on the characteristics of the introduced species but also on the abundance of the native population, its range relative to that of the introduced species, its physiological relationship to the environment, and its interactions with prey, competitors or predators—factors that in turn may be affected by climate change. Moreover, some invasive species are 'ecosystem engineers,' capable of modifying the physical or chemical properties of an ecosystem (Crooks 2002). It is also likely that climate change will alter human behaviours, which could affect both the probability of transporting invasive species to a new area (e.g., by vectors such as shipping or aquaculture transfers), and alter anthropogenic pressures (e.g., fishing, shoreline development, environmental disturbance) on both native and invasive species and other components of the ecosystem.

The purpose of this review is to establish a context for predictions of the invasive species–climate change interaction in marine and estuarine environments of Atlantic Canada: specifically, to review the literature that supports predictions of impacts, vulnerabilities and opportunities associated with the predicted consequences of climate change on invasive species.

7.3 PREDICTING THE EFFECTS OF CLIMATE CHANGE ON INVASIVE SPECIES IN ATLANTIC CANADA

The ability of a species to be successfully introduced, and subsequently to become invasive, is closely related to the characteristics of the novel habitat relative to the requirements of the species. A series of environmental filters determines the probability of success at each step or stage of introduction: arrival (the result of transport), survival of the arriving individuals in the new environment, establishment (reproduction and population growth), and dispersal from the point of introduction (Fig. 7–1). Whether a species is then considered invasive depends on its interactions with the biotic and abiotic components of its new environment, as well as its socio-economic impacts, all of which are potentially influenced by climate. Some ways in which climate change might affect these environmental filters will be discussed in the contexts of risks to Atlantic Canada. The present review will be structured in the context of the environmental filters or steps required for a successful invasion.

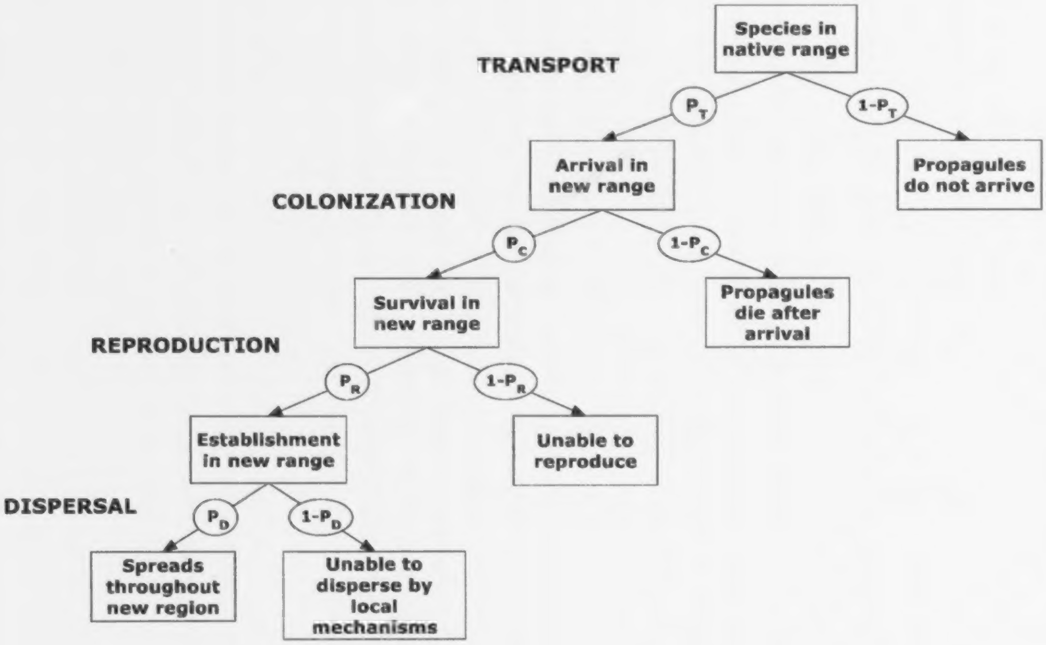
Species in native range
TRANSPORT
P_T
$1-P_T$
Arrival in new range
Propagules do not arrive
COLONIZATION
P_C
$1-P_C$
Survival in new range
Propagules die after arrival
REPRODUCTION
P_R
$1-P_R$
Establishment in new range
Unable to reproduce
DISPERSAL
P_D
$1-P_D$
Spreads throughout new region
Unable to disperse by local mechanisms

Figure 7–1 Conceptual model illustrating the role of environmental filters at four steps of introduction of a species to a novel environment: (1) Transport, (2) Colonization, (3) Reproduction, (4) Dispersal. The probability of successful transition to the next level, i, is indicated as P_i. Failure to transition occurs at a probability of $1-P_i$. The terminology and framework presented here were derived from Harley et al. (2006), Moore (2006), Vermeij (1996), Williamson (2006) and Williamson and Fitter (1996).

7.4 TRANSPORT (SPECIES IN SOURCE REGION → ARRIVAL IN TARGET REGION

There is a risk that changes in human transport may increase or decrease propagule pressure. In the case of regions that are newly connected by a transport vector, P_T (the probability of successful transport) may increase to a value > 0. If regions are no longer connected, the value of P_T should decrease to 0. A similar result should theoretically occur if propagule pressure is increased or decreased beyond a threshold that allows for successful inoculation (Tobin et al. 2011).

Probability of transport determines propagule pressure, which depends on the uptake of propagules in the source region, characteristics of the transport vector between a source and target region (climate change could link geographic areas previously separated), and the survival rate of propagules during transport (climate change could affect biological processes associated with transport events). Historically, the most common vectors (pathways) for invasive species in marine environments have been shipping (e.g., ballast water, hull fouling) and aquaculture (e.g., escape of cultured introductions into the wild, fellow travellers on aquaculture transfers). A definition used by most invasive species is that, transport vectors for an introduction must be anthropogenic, since the species is overcoming a dispersal barrier that was not passable by natural mechanisms, and that poleward movements of organisms responding to warmer temperatures represent migration rather than invasion. One consequence of climate change may be the blurring of this distinction between anthropogenic introduction and range expansion through migration, as climate-related limits shift (Walther et al. 2009). Similarly, it is unclear whether climate-related catastrophic events such as the 2011 tsunami in Japan, resulting in the arrival of human debris supporting viable propagules of non-indigenous species on the west coast of North America, would be considered as natural or anthropogenic dispersal. Many scientists consider this to represent a species inoculation, despite the vector having been 'natural' climate-related causes. Determining the role of humans in observed range alterations may become increasingly difficult over time, which may have implications for regulatory issues or international agreements.

Climate change could alter the probability of transport in any of the following ways:

- Pathways of international transport could change. One example of this is the opening of Arctic trade routes, which is likely to increase voyages from the North Pacific to Atlantic Canada, but other changes could occur globally as well. It is possible that patterns of trade may alter so voyages originate from ports not presently serving as important sources of propagules to Canada. A substantial number of vessels already travel to, or through, Atlantic Canada. During the 12-month period March 2010 to February 2011, the Canadian Coast Guard's Long Range Identification and Tracking system recorded 29,761 tracks of commercial vessels (gross tonnage > 300 tonnes) transiting Atlantic Canada (Koropatnick et al. 2012). In recent decades, changes in patterns of trade have been reflected in species from the North Pacific dominating introductions into Atlantic Canada, whereas previously most introductions were of northern European species (A. Locke and J.M. Hanson, unpub. data). It is not clear to what extent climate-related changes in the number or patterns of commercial vessels will change propagule pressure in Atlantic Canada. It is thought that many Canadian ports already have substantial connections to the global shipping network. For example, the Great Lakes are already connected to most active global ports by no more than two ship voyages, and to all global ports by no more than five voyages (Keller et al. 2011). No comparable analysis has been conducted for ports in Atlantic Canada

- Longer shipping seasons will increase the number of voyages that can be completed into areas that are presently ice-covered for much of the winter, such as the Gulf of St. Lawrence. Ice cover has been declining in the Gulf of St. Lawrence. During the period 1981 to 2010, the least amount of ice encountered in a single season occurred in 2009-10 (Canadian Ice Service 2010). This could permit greater access to ports in the Gulf. An increase in ships transiting through Atlantic Canada en route to the Great Lakes may also occur as a result of longer seasons. Between 1982-1986 and 2002-2006, the average open season for the Montreal-Lake Ontario section of the St. Lawrence Seaway increased by 10 days (Millerd 2007).
- Climate change could alter patterns of tourism. This may result in more recreational vessels or cruise ships arriving annually, or these may arrive from parts of the world from which relatively little traffic now arrives to Atlantic Canada. Recreational boating is a high-risk vector contributing both to the primary introduction of species to Canada, and the secondary dispersal of species from their initial point of introduction (Clarke Murray et al. 2011; Darbyson et al. 2009; Lacoursière-Roussel et al. 2012). For the most part, species transported by these vectors would be associated with fouling of vessel surfaces rather than ballast water releases.
- Loss of Arctic sea ice could increase use of routes through the Arctic and substantially reduce travel time for some ships. This could increase survival rates of organisms in ballast water and ships' hulls by reducing starvation, predation and low light availability during the voyage (Pyke et al. 2008). Ocean circulation could also change as a result of the loss of Arctic ice. An example of a species which has already expanded its range through the Arctic due to such a change is the marine diatom *Neodenticula seminae*, which was found in the Atlantic Ocean in 1999. This species is thought to have migrated from the North Pacific to the North Atlantic as a result of diminishing ice cover which opened a temporary passageway (Reid et al. 2007). An

alternative explanation may be that the diatom was carried in ballast water of a vessel using a newly-opened Arctic passage.

- Changing conditions could lead to demand for aquaculture or recreational fishery species novel to Atlantic Canada, with an increased risk of viable population growth of escapees as conditions change to more closely resemble their habitat requirements. New areas may become suitable for culture of previously introduced species. It is also likely that previously introduced cultured species, not expected or formerly unable to establish viable wild populations at the point of introduction, may become more competent to do so. Examples of aquaculture species that have unexpectedly established wild populations include European oyster (*Ostrea edulis*) in Nova Scotia and Pacific oyster (*Crassostrea gigas*) in northern Europe (Nehring 2003). The shift in recruitment success of Pacific oyster is particularly well documented. Introduced in the 1920s and again in the 1960s, it had been unable to reproduce in northern European waters, but since approximately 1989 has established extensive reefs that threaten some native species (Pederson et al. 2011).

7.5 COLONIZATION (ARRIVAL IN TARGET REGION → SURVIVAL IN TARGET REGION)

There is a risk that the probability of colonization, P_C, may increase for some currently unsuccessful non-native species if conditions become more like the species' native range or biotic constraints (e.g., competition, predation) are reduced.

Probability of colonization reflects the ability of a species to survive (but not yet to reproduce or disperse) at the point of introduction in the target region. This could result in a population established, for example, within a particular port or estuary, and having local impacts in that area but only for the lifetime of the introduced individuals. Alternatively, if subsequent steps in the introduction were successful, a long-term introduction could occur.

Climate change could alter the probability of colonization in any of the following ways:

- If environmental conditions change such that there is a closer match between the source and target region, the result may be a decrease in physiological stress and increase in the probability of survival. Projected climate changes include not only temperature, but many other variables that constitute a species' environmental niche. Climate-induced changes in near-coastal and estuarine waters are of particular interest because these often serve as initial sites of introduction of non-indigenous species (Zaiko et al. 2007; Pederson et al. 2011). Key drivers of climate change likely to affect these waters include sea level change; alterations in precipitation patterns and subsequent delivery of freshwater, nutrients and sediment; increased ocean temperature; alterations in circulation patterns; changes in frequency and intensity of coastal storms; and increased levels of atmospheric carbon dioxide (Scavia et al. 2002). Effects on shorelines, wetlands, coastal development, disturbances to estuaries (to productivity, stratification and residence time), eutrophication, ocean acidification, vertical zonation shifts caused by UV radiation, synergistic effects of UV radiation with contaminants, and development or expansion of nearshore zones of hypoxia and anoxia are predicted (Scavia et al. 2002; Peachey 2005; Pörtner and Langenbuch 2005; Harley et al. 2006; Doney et al. 2009). The potential for complex biogeochemical feedback mechanisms makes it difficult to precisely predict which of these changes may occur (IPCC 2001).

- Overwintering mortality may be an obstacle to the survival of many non-indigenous species in Atlantic Canada. As an example, for decades it has been documented that dozens of species were carried to the southern shores of Nova Scotia in Gulf Core rings, have lived for brief periods but have not survived their first winter (Markle et al. 1980; Wroblewski and Cheney 1984). If warmer winters occur, this barrier may be removed for many species. Similarly, changes in winter conditions may alter the risk of survival of organisms that may be released in ballast water in the Gulf of St. Lawrence alternative ballast water exchange zone in winter. Commercial vessels entering Canadian waters from outside the Exclusive Economic Zone are normally required to conduct a ballast water exchange at least 200 nautical miles from shore to reduce the risk of species inoculations to Canadian waters, but the Laurentian Channel is accepted as an emergency alternative exchange zone from December 1 to May 1 (Minister of Justice, 2012). Those dates were proposed as representing a period when offshore exchanges might compromise the safety of vessels, when cold temperatures in the Gulf of St. Lawrence would minimize the risk of survival of most released organisms (Gilbert et al. 2004). Risks associated with three ballast water exchange zones recommended for year-round use on the Scotian Shelf and Gulf of Maine/Bay of Fundy (Transport Canada, 2013) would also most likely be affected.
- Climate-driven changes in the marine systems of the North Atlantic have most often been recorded at the boundaries of biogeographic regions, where species of warm- and cold-water origins overlap and reach their respective limits of distribution (Mieszkowska et al. 2006; Beaugrand et al. 2009). Poleward distribution shifts are likely to be greater at these boundaries than elsewhere. Three major bioregions have been identified in Atlantic Canada, with boundaries at the Strait of Belle Isle; the Cabot Strait and a line extending from its midpoint in a southeasterly direction; and to the south, near Georges Bank (DFO 2009). Present temperatures and predicted near-future increases in

thermal stress do not necessarily vary consistently with latitude in coastal marine systems (Helmuth et al. 2002) and organisms could be most at risk in 'hotspots' well removed from the range edge (Harley et al. 2006). The southern Gulf of St. Lawrence (Magdalen Shallows) is probably such a 'hotspot': it is biogeographically distinct from the rest of the Gulf of St. Lawrence, already functions as a reservoir of warm-water fauna and flora more typical of waters south of Cape Cod, and is separated from the nearest populations of these organisms by hundreds of kilometres of colder waters (Bousfield and Thomas 1975; Voutier and Hanson 2008).

- Biotic interactions (e.g., strength of interaction with prey, competitors, predators, parasites or diseases) will also influence the probability of survival (Harley et al. 2006). The effects of climate change are extremely complex and difficult to predict. They could change due to physiological, morphological and behavioural effects; changes in per capita interaction strengths; or changes in population size of interacting populations.
- Emergent ecological responses could include alterations in species distributions, biodiversity, productivity, or microevolutionary processes (Harley et al. 2006).

7.6 REPRODUCTION (SURVIVAL IN TARGET REGION → ESTABLISHMENT IN TARGET REGION)

There is a risk that some currently unsuccessful non-native species will be able to reproduce and establish persistent populations if conditions change to more closely resemblethe species' native range or biotic constraints (e.g., competition, predation) are reduced.

Probability of reproduction reflects the environmental (biotic and abiotic) conditions associated with local population growth. The filter at this step is the effect of the environment on the rate of population growth at the point of introduction.

Climate change could alter the probability of reproduction in any of the following ways:

- The range of physico-chemical conditions allowing reproduction may be narrower than those allowing survival of the species. If climate change results in a closer environmental match to conditions in the source region, reproduction may become possible in populations that when inoculated into an area in previous years were only able to survive for a single adult lifespan. For example, adult green crabs (*Carcinus maenas*) survive salinities of 4 to 52‰ but larvae cannot mature at salinities < 20‰ (Anger et al 1998; Cohen and Carlton 1995). Ontogenetic shifts in habitat use and environmental tolerance/preference are common in marine species. Many pelagic fish species spawn for a limited time each year in areas that are much smaller than their typical distribution, reflecting narrower habitat tolerances for spawning (Robinson et al. 2011).

- Biotic interactions are also important in determining if reproduction can occur. As with physico-chemical environment, the nutritional requirements or habitat requirements for a species to reproduce may be different from those it needs to simply survive. Climate change could affect the ability of invasive species to obtain food. For example, if climate change were to reduce native species populations leading to a reduction in competitive pressure, non-indigenous species may be able to obtain a greater food supply leading to larger clutches of eggs or reduced time between clutches. Basic physiology suggests, and this has been demonstrated in cnidarians, that reproductive rates are affected by temperature and salinity both directly through metabolism and indirectly through rates of prey capture (Purcell 2005).
- The duration of the 'lag phase' of population growth in introduced species (Crooks and Soulé 1999) could be altered by climate change. Following this period of adaptation or selection to local environmental conditions by an introduced species, population growth is sometimes very rapid. This may explain how some species that establish small and apparently non-invasive populations upon arrival later become aggressively invasive (Crooks and Soulé 1999). Generally such adaptation takes place within a few years of arrival, but one introduced barnacle occurred in the North Sea for 50 years before becoming invasive. Its subsequent rapid population growth and present dominance over native barnacles is attributed to climatic warming (Witte et al. 2010). Depending on whether climate change shifts local conditions closer or farther from source conditions to which a species is adapted, the lag time could be lengthened or shortened for a given species. Local temperature adaptation appears to be common in introduced species. Populations of the green alga *Codium fragile fragile* in Maine tolerate colder temperatures than those found further south in the US (Carlton and Scanlon 1985). Minimum temperature tolerance of the tunicate *Botrylloides* sp. varies between sites separated by < 60 km (Grosholz 2001).

7.7 DISPERSAL (ESTABLISHMENT IN TARGET REGION → SPREAD TO NEW AREAS IN TARGET REGION)

There is risk that some currently unsuccessful non-native species will be able to disperse to new areas in Atlantic Canada from the initial point of introduction. Once species establish at the point of introduction, the next stage of invasion is local dispersal into new areas within the target region. This is often referred to as 'secondary spread' following the initial (often international) 'primary introduction'. Vectors of secondary spread are typically different from the long-distance transport mechanisms (normally anthropogenic) of primary introduction. Secondary spread may take place by natural (e.g., drift on oceanographic currents, or active dispersal by larger organisms such as fishes or crabs) or anthropogenic (local shipping and boating, intentional or unintentional transfers on aquaculture or fishing gear, etc.) vectors.

Climate change could alter the probability of dispersal, especially for species that disperse on ocean currents. Currents in the North Atlantic Ocean are intimately linked to climate, and may already incorporate the influence of anthropogenic activities in increased variability of the North Atlantic Oscillation (Holliday et al. 2011a, 2011b). Changes in the direction and intensity of currents have major implications for recruitment. In addition, warmer ocean temperatures are likely to reduce the development times of marine larvae and change the duration and pattern of their spread by currents. The development time of green crab (*Carcinus maenas*) zoeae decreased from 51.9 days at 10°C to 25.4 days at 25°C (Nagaraj 1993), which would modify the distance of dispersal, possibly allowing the juveniles to settle into a more concentrated receiving area.

7.8 DISCUSSION

The examples presented in the previous section suggest that an increase in the number of invasive species in marine waters of Atlantic Canada will most likely accompany predicted climate change. A rise in temperature could lead to new species expanding their ranges into the country, especially from southern origins (e.g., from American coastal waters) or through the Arctic, and/or existing species expanding their ranges within the country (Smith et al. 2012). Coastal and estuarine waters are the most vulnerable sites of introduction, especially in man-made features, such as ports, marinas and aquaculture facilities (Zaiko et al. 2007; Pederson et al. 2011).

With increasing numbers of established invader species, the rate of invasion has accelerated in a number of well-studied water bodies (Carlton 1996; Cohen and Carlton 1998; Simberloff and Van Holle 1999). This situation, known as ‘invasional meltdown,’ may involve facilitation of additional invaders by those already established in the area. There are several examples in Atlantic Canada. Facilitation by green crab may have been a contributing factor in the establishment of the clubbed tunicate *Styela clava* in Prince Edward Island estuaries (Locke et al. 2007), and the invasion of the bryozoan *Membranipora membranacea* most likely facilitated the takeover of kelp beds in Nova Scotia by the green alga *Codium fragile fragile* (Saier and Chapman 2005). Green crab and several other non-indigenous species presently established in Atlantic Canada, including the common periwinkle *Littorina littorea* (present in Atlantic Canada since the 1850s), are ecosystem engineers (Crooks 2002). Such species are of special concern when assessing the risk of impacts of invaders, since they can alter the ecological services provided by the ecosystem as well as facilitating the establishment of other invaders.

Management strategies developed for the invasive species that have become established in Atlantic Canada in the past decade may be insufficient to deal with a possible influx of new species, or with enhanced population growth of the existing assemblage. Currently, there is little demand for management of invasive species in Atlantic Canada. The major management activity is the use of mechanical and chemical methods to control invasive tunicates on bivalve aquaculture sites in the warm estuaries of Prince Edward Island (Locke et al. 2009). These methods may become less effective or may need to be used more often, increasing costs to bivalve growers, if increased survival rates, shorter generation times and/or longer growing seasons result in heavier tunicate infestations. Additionally, tunicate control may be required over a wider area, for example temperatures in southern Nova Scotian estuaries where bivalve aquaculture is conducted are typically cool enough at present (< 18°C) that little or no tunicate management is needed, but this may change in future. Stachowicz et al. (2002) have identified a summer water temperature of ~19 °C as a threshold above which several invasive tunicates (including species recently arrived in Atlantic Canada) are able to form large populations and outcompete native species.

Positive ecosystem consequences have occasionally been documented from invasions, although the functioning of the estuaries in which these occurred may already have been damaged by anthropogenic disturbance. Total primary production in Willapa Bay, WA, increased > 50% with the introduction of non-indigenous vascular plants, and total secondary production increased 250% due to introduction of non-indigenous bivalves. Environments with empty niches were colonized by species that filled novel roles in the ecosystem, with implications for habitat, detritus and filtration (Ruesink et al. 2006).

Some invasive marine species support commercial or recreational fisheries. In Atlantic Canada, the common periwinkle *Littorina littorea* and the alga *Furcellaria lumbricalis* are commercially harvested (DFO 1998; Bird et al. 1991). An experimental fishery on green crab (*Carcinus maenas*) is currently (2012) taking place in southern Nova Scotia, with the crabs sold as bait for the American lobster (*Homarus americanus*) fishery. Some other invaders of Atlantic Canada, e.g., the clubbed tunicate *Styela clava*, are commercially harvested and even farmed in other countries (Karney and Rhee 2009).

The complexity of the invasive species-climate change dynamic is such that detailed prediction of the outcome is not possible. Overall, the likelihood is that the net effect of the climate change-invasive species interaction in Atlantic Canada will be negative in terms of impacts on ecosystems and livelihoods. It is very unlikely that the net effect will be positive, although some species may be suitable for commercial or recreational harvest.

7.9 REFERENCES

Anger K, Spivak E, Luppi T (1998) Effects of reduced salinities on development and bioenergetics of early larval shore crab, *Carcinus maenas*. Journal of Experimental Marine Biology and Ecology 220: 287-304.

Beaugrand G (2009) Decadal changes in climate and ecosystems in the North Atlantic Ocean and adjacent seas. Deep-Sea Research II 56: 656-673.

Bird CJ, Saunders GW and McLachlan J (1991) Biology of *Furcellaria lumbricalis* (Hudson) Lamouroux (Rhodophyta: Gigartinales), a commercial carrageenophyte. Journal of Applied Phycology 3: 61-82

Blackburn TM, Duncan RP (2001) Determinants of establishment success in introduced birds. Nature 414: 195-197.

Bousfield EL, Thomas MLH (1975) Postglacial changes in distribution of littoral marine invertebrates in the Canadian Atlantic region. Proceedings of the Nova Scotian Institute of Science 27 (Supplement 3): 47-60.

Canadian Ice Service (2010) Sea ice climatic atlas. East coast, 1981-2010. Environment Canada. 248 pp. http://www.ec.gc.ca/Publications/8DFED3F9-4BD6-49F3-9ACA-F9AA9F52A96D/East_Coast_2010_E.pdf

Carlton JT (1996) Pattern, process and prediction in marine invasion ecology. Biological Conservation 78: 97-106.

Carlton JT, Scanlon JA (1985) Progression and dispersal of introduced alga: *Codium fragile ssp. tomentosoides (Chlorophyta)* on the Atlantic coast of North America. Botanica Marina 28: 155-165.

CCFAM (2004) A Canadian Action Plan to address the threat of Aquatic Invasive Species. Aquatic Invasive Species Task Group, Canadian Council of Fisheries and Aquaculture Ministers. Sept. 2004. 26 p.

Clarke Murray C, Pakhomov EA, Therriault T (2011) Recreational boating: A large unregulated vector transporting marine invasive species. Diversity and Distributions 17: 1161-1172.

Cohen AN, Carlton JT (1995) Nonindigenous aquatic species in a United States estuary: A case study of the biological invasions of the San Francisco Bay and Delta. Report to the US Fish and Wildlife Service, Washington, DC, and Connecticut Sea Grant.

Cohen AN, Carlton JT (1998) Accelerating invasion rate in a highly invaded estuary. Science 279: 555-558.

Crooks JA (2002) Characterizing ecosystem-level consequences of biological invasions: the role of ecosystem engineers. Oikos 97: 153-166

Crooks JA, Soulé (1999) Lag times in population explosions of invasive species: causes and implications. Pages 103-126 in OT Sandlund et al. (eds.) Invasive species and biodiversity management. Kluwer, NY.

Darbyson E, Locke A, Hanson JM, Willison JHM (2009) Marine boating habits and the potential for spread of invasive species in the Gulf of St. Lawrence. Aquatic Invasions 4: 87-94.

DFO (1998) Periwinkle (*Littorina littorea*). DFO Science Stock Status Report C3-46. 5p.

DFO (2009) Development of a framework and principles for the biogeographic classification of Canadian marine areas. Canadian Science Advisory Secretariat Science Advisory Report 2009/056.

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO_2 problem. Annual Review of Marine Science 1: 169-192.

Gilbert M, Simard N, Saucier FN (2004) Suitability of the Gulf of St. Lawrence as an alternate zone for ballast water exchange by foreign ships proceeding up the St. Lawrence Seaway. In: Pederson J (ed.) Ballast water exchange: Exploring the feasibility of alternate ballast water exchange zones in the North Atlantic. Massachusetts Institute of Technology Sea Grant College Program, Publication 04-2. pp. 71-78.

Grosholz ED (2001) Small spatial-scale differentiation among populations of an introduced colonial invertebrate. Oecologia 129: 58-64.

Harley CDG, Hughes AR, Hultgren KM, Miner BG, Sorte CJB, Thornber CS, Rodriguez LF, Tomanek L, Williams SL (2006) The impacts of climate change in coastal marine systems. Ecology Letters 9: 228-241

Helmuth B, Harley CD, Halpin PM, O'Donnell M, Hofmann GE, Blanchette CA (2002) Climate change and latitudinal patterns of intertidal thermal stress. Science 298: 1015-1017.

Holliday NP, Hughes SL, Borenäs K, Feistel R, Gaillard F, Lavìn A, Loeng H, Mork KA, Nolan G, Quante M, Somavilla R (2011a) Long-term physical variability in the North Atlantic Ocean. In: Reid PC, Valdes (eds.) ICES status report on climate change in the North Atlantic. ICES Cooperative Research Report 310: 21-46.

Holliday NP, Quante M, Sherwin T, Nolan G, Mork KA, Cannaby H, Berry D (2011b) North Atlantic circulation and atmospheric forcing. In: Reid PC, Valdes (eds.) ICES status report on climate change in the North Atlantic. ICES Cooperative Research Report 310: 8-20.

IPCC (2001) Climate change 2001, synthesis report. A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Karney RC, Rhee WY (2009) Market potential for *Styela clava*, a non-indigenous pest invading New England coastal waters. Aquatic Invasions 4: 295-297.

Keller RP, Drake JM, Drew MB, Lodge DM (2011) Linking environmental conditions and ship movements to estimate invasive species transport across the global shipping network. Diversity and Distributions 17: 93-102.

Koropatnick T, Johnston SK, Coffen-Smout S, Mcnab P, Szeto A (2012) Development and applications of vessel traffic maps based on Long Range Identification and Tracking (LRIT) data in Atlantic Canada. Canadian Technical Report of Fisheries and Aquatic Sciences 2966.

Lacoursière-Roussel A, Bock DG, Cristescu ME, Guichard F, Girard P, Legendre P, McKindsey CW (2012) Disentangling invasion processes in a dynamic shipping-boating network. Molecular Ecology 21: 4227-4241.

Locke A, Hanson JM, Ellis KM, Thompson J, Rochette R (2007) Invasion of the southern Gulf of St. Lawrence by the clubbed tunicate (*Styela clava* Herdman): Potential mechanisms for invasions of Prince Edward Island estuaries. Journal of Experimental Marine Biology and Ecology 342: 69-77.

Locke A, Hanson JM, MacNair NG, Smith AH (2009) Rapid response to non-indigenous species. 2. Case studies of invasive tunicates in Prince Edward Island. Aquatic Invasions 4: 249-258.

Markle DF, Scott WB, Kohler AC (1980) New and rare records of Canadian fishes and the influence of hydrography on resident and non-resident Scotian Shelf ichthyofauna. Canadian Journal of Fisheries and Aquatic Sciences 37: 49-65.

Mieszkowska N, Leaper R, Moore P, Kendall MA, burrows MT, Lear D, Poloczanska E, et al. (2005) Marine biodiversity and climate change: Assessing and predicting the influence of climatic change using intertidal rocky shore biota. Marine Biological Association Occasional Publication No. 20. 53 pp. (in Pederson)

Millenium Ecosystem Assessment (2005) Ecosystems and human well-being: Biodiversity synthesis. World Resources Institute, Washington, DC. 100p. http://www.millenniumassessment.org/documents/document.354.aspx.pdf

Millerd F (2007) Global climate change and Great Lakes international shipping. Committee on the St. Lawrence Seaway, Transportation Research Board Special Report 291. Great Lakes shipping, trade and aquatic invasive species. http://onlinepubs.trb.org/onlinepubs/sr/sr291_millerd.pdf

Minister of Justice (Canada) (2012) Ballast Water Control and Management Regulations SOR/2011-237. Current to December 10, 2012. http://laws-lois.justice.gc.ca

Moore JE (2006) Documentation for Biological Risk Assessment Software. (QBRAT v. 2 – DFO's Quantitative Biological Risk Assessment Tool, DFO Centre for Expertise in Aquatic Risk Assessment, Burlington ON). JEMSys Software Systems Inc., Dundas ON.

Nagaraj M (1993) Combined effects of temperature and salinity on the zoeal development of the green crab, *Carcinus maenas* (Linnaeus, 1758) (Decapoda: Portunidae). Scientia Marina 57: 1-8.

Nehring S (2003) Alien species in the North Sea: invasion success and climate warming. Ocean Challenge 13(3): 12-16.

Parker IM, Simberloff D, Lonsdale WM, Goodell K, Wonham M, Kareiva PM, Williamson MH, Von Holle B, Moyle PB, Byers JE, Goldwasser L (1999) Impact: toward a framework for understanding the ecological effects of invaders. Biological Invasions 1: 3-19.

Peachey RBJ (2005) The synergism between hydrocarbon pollutants and UV radiation: a potential link between coastal pollution and larval mortality. Journal of Experimental Marine Biology and Ecology 315: 103-114.

Pederson J, Mieszkowska N, Carlton JT, Gollasch S, Jelmert A, Minchin D, Occhipinti-Ambrogi A, Wallentinus I (2011) Climate change and non-native species in the North Atlantic. In: Reid PC, Valdes (eds.) ICES status report on climate change in the North Atlantic. ICES Cooperative Research Report 310: 174-190

Pörtner HO, Langenbuch M (2005) Synergistic effects of temperature extremes, hypoxia and increases in CO_2 on marine animals: from Earth history to global change. Journal of Geophysical Research 110: C09S10, doi:10.1029/2004JC002561.

Purcell JE (2005) Climate effects on formation of jellyfish and ctenophore blooms: a review. Journal of the marine Biological Association of the U.K. 85: 461-476.

Pyke CR, Thomas R, Porter RD, Hellmann JJ, Dukes JS, Lodge DM, Chavarria G (2008) Current practices and future opportunities for policy on climate change and invasive species. Conservation Biology 22: 585-592.

Reid PC, Johns DG, Edwards M, Starr M, Poulins M, Snoeijs P (2007) A biological consequence of reducing Arctic ice cover: arrival of the Pacific diatom, Neodenticula seminae, in the North Atlantic for the first time in 800,000 years. Global Change Biology 13: 1910-1921.

Robinson LM, Elith J, Hobday AJ, Pearson RG, Kendall BE, Possingham HP, Richardson AJ (2011) Pushing the limits in marine species distribution modelling: lessons from the land present challenges and opportunities. Global Ecology and Biogeography 20: 789-802.

Ruesink JL, Feist BE, Harvey CJ, Hong JS, Trimble AC, Wisehart LM (2006) Changes in productivity associated with four introduced species. Marine Ecology Progress Series 311: 203-215.

Saier B, Chapman AS (2005) Crusts of the alien bryozoan *Membranipora membrancea* can negatively impact spore output from native kelps (*Laminaria longicruris*). Botanica Marina 47: 265-271.

Scavia D, Field JC, Boesch DF, Buddemeier RW, Burkett V, Cayan DR, fogarty M, Harwell MA, Howarth RW, Mason C, Ro\eed DJ, Royer TC, Sallenger AH, Titus JG (2002) Climate change impacts on U.S. coastal and marine ecosystems. Estuaries 25: 149-164.

Simberloff D, Van Holle B (1999) Positive interactions of nonindigenous species: invasional meltdown? Biological Invasions 1; 21-32.

Smith AL, Hewitt N, Klenk N, Bazely DR, Yan N, Wood S, Henriques I, MacLellan JI, Lipsig-Mummé C (2012) Effects of climate change on the distribution of invasive alien species in Canada: a knowledge synthesis of range change projections in a warming world. Environmental Reviews 20: 1-16..

Stachowicz JJ, Terwin JR, Whitlatch RB, Osmand RW (2002) Linking climate change and biological invasions: Ocean warming facilitates nonindigenous species invasions. Proceedings of the National Academy of Sciences 99: 15497-15500.

Tobin PC, Berec L, Liebhold AM (2011) Exploiting Allee effects for managing biological invasions. Ecology Letters 14: 615-624.

Transport Canada (2013) A guide to Canada's Ballast Water Control and Management Regulations TP 13617E. http://www.tc.gc.ca/eng/marinesafety/tp-tp13617-menu-2138.htm accessed 2 January 2013.

Vermeij GJ (1996) An agenda for invasion biology. Biological Conservation 78: 3-9.

Voutier JL, Hanson JM (2008) Abundance, distribution, and feeding of lady crab in the southern Gulf of St. Lawrence. Aquatic Ecology 42: 43-60.

Walther GR, Roques A, Hulme PE, Sykes MT, Pyšek P, Kűhn I, Zobel M, Bacher S, Botta-Dukát Z, Bugmann H, Czúcz B, Dauber J, Hickler T, Jarošik V, Kenis M, Klotz S, Minchin D, Moora M, Nentwig W, Ott J, Panov VE, Reinekin B, Robinet C, Semenchenko V, Solarz W, Thuiller W, Vilà M, Vohland K, Settele J (2009) Alien species in a warmer world: Risks and opportunities. Trends in Ecology and Evolution 24: 686-963.

Williamson MH, Brown KC, Holdgate MW, Kornberg H, Southwood R, Mollison D (1986) The analysis and modelling of British invasions. Philosophical Transactions of the Royal Society B 314: 505-522.

Williamson M (2006) Explaining and predicting the success of invading species at different stages of invasion. Biological Invasions 8: 1561-1568.

Williamson MH, Fitter A (1996) The characters of successful invaders. Biological Conservation 78: 163-170.

Witte S, Buschbaum C, van Beusekom JEE, Reise K (2010) Does climatic warming explain why an introduced barnacle finally takes over after a lag of more than 50 years? Biological Invasions 12: 3579-3589.

Wroblewski JS, Cheney J (1984) Ichthyoplankton associated with a warm core ring off the Scotian Shelf. Canadian Journal of Fisheries and Aquatic Sciences 41: 294-303.

Zaiko A, Olenin S, Daunys D, Nalepa T (2007) Vulnerability of benthic habitats to the aquatic invasive species. Biological Invasions 9: 703-714.

Chapter 8 Climate change impacts and vulnerability of marine species at risk in the Atlantic basin of Canada: A screening level analysis of climate change impacts and vulnerability

R.D. Walmsley

Bedford Institute of Oceanography, Fisheries and Oceans Canada, P.O. Box 1006, Dartmouth, NS, B2Y 4A2

*Correspondence: Nancy.Shackell@dfo-mpo.gc.ca

Suggested Citation:

Walmsley, R.D. 2013. Climate change impacts and vulnerability of marine species at risk in the Atlantic basin of Canada: A screening level analysis of climate change impacts and vulnerability. Ch. 8 (p. 256–289) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

8.1 INTRODUCTION AND OBJECTIVES

Climate change, with its multiple potential impacts on natural resources, has been identified as a significant long-term sustainability issue that requires assessment and management attention in Canada (Lemmen *et al*. 2008). In 2005 INTERIS identified six categories of climate change risk factors that were of strategic interest to the Canadian Department of Fisheries and Oceans (DFO) in terms of its mandate for the management of Canadian waters and aquatic resources (INTERIS 2005). One of the identified areas, "Species Reorganization and Displacement", was considered as important by INTERIS (2005) because *"— there was a risk that climate change will affect DFO's ability to to protect species diversity and species at risk"*. Recent follow up assessments have continued to support the opinion that climate change is indeed a key potential risk factor in influencing diversity and species at risk in Canada's ocean areas (INTERIS 2012, Royal Society of Canada 2012).

The DFO is currently undertaking a nation-wide climate change initiative (Aquatic Climate Change Adaptation Services Program- ACCASP) aimed at developing new science knowledge to support the development of adaptation tools and strategies that will enable the integration of climate change considerations into the delivery of the Department's programs and policies (http://www.dfo-mpo.gc.ca/science/oceanography-oceanographie/accasp/index-eng.html). The three activity areas of ACCASP include:

1. Development of a series of large basin risk assessments;
2. Producing new knowledge on climate change impacts; and
3. Development of applied science-based adaptation tools across the Department's program activities and strategic outcomes.

In Canada, "Species at Risk" represents a group of species that has attracted attention because their populations have gone into unacceptable decline, mainly because of anthropogenic activity (Royal Society of Canada 2012). Screening and assessment of relevant species is overseen by a federally-appointed Committee on the Status of Endangered Wildlife in Canada (COSEWIC) that operates under the the *Species at Risk Act* (SARA) (COSEWIC 2012). The DFO is responsible for overseeing the monitoring and management of aquatic species that have been listed under SARA. Accordingly, as part of the nation-wide ACCASP program, it was decided to include a basin-level Impact and Vulnerability (I&V) assessment of species at risk. The intention is that information and perspectives generated by this assessment should contribute to furthering the overall objectives of ACCASP and the mainstreaming of climate adaptation into the DFO's strategic and operational activities.

The primary objective of this report has been to generate relevant information and perspectives that contribute to the objectives of ACCASP, and which can be used by the DFO's "species at risk" sector in the furthering of strategic and operational approaches to reducing possible risks created by climate change. This has been done by providing information on:

- Aspects of I&V approaches that are important;
- Potential climate change stressors;
- The current status of marine species at risk in the Atlantic Basin area;
- Attributes of the respective species at risk that might affect their exposure, vulnerability and resilience to climate change factors that are of interest;
- A preliminary screening-level impacts and vulnerability assessment; and
- Identification of any relevant anticipated changes and impacts that might be brought about by climate change.

It is accepted that there are currently other parallel studies within ACCASP that are dealing with both similar, and different, aspects of climate change – there will therefore be diverse opinion and many other approaches to those presented in this report. Because of the multi-faceted and diverse impacts of climate change, and the absence of detailed research information on each of the species, this study has at best only been able to scratch the surface on this topic. The document should therefore not be seen as a definitive or authoritative product, but rather as one that contributes to understanding the wider picture.

8.2 BACKGROUND TO THIS ASSESSMENT

8.2.1 ACCASP Guidelines and Approach to the Atlantic Basin

Guidelines were provided to ACCASP program participants during a DFO workshop convened in late January 2012. Contributors were requested to take note of the following:

1. The climate change summary provided by a Trends and Projections (T&P) Group would provide the starting point for contributors in terms of the magnitude of change to expect for specific variables. The direction of change can be anticipated based on general expectations already in the literature before a T&P preliminary report is delivered.
2. The climate change stressors that were of main interest to DFO included: temperature (surface and bottom), salinity, density stratification, and sea ice.
3. The report should attempt to be relevant to the appropriate DFO sector.
4. An attempt should be made to strike a balance between basin-scale and regional patterns of variation in climate change and impact.
5. Engage and consult with relevant people from other DFO sectors who might provide information or opinion on your topic.
6. Research and identify the vulnerability of the assigned biological targets. The DFO Sectors will then use this information to assess and develop their own adaptation response based on the DFO's PAA.
7. Use case study summaries to illustrate impacts in relation to Climate Change: Make use of "case studies" – where information, knowledge and understanding are high. Case studies should also consider positive impacts of climate change (i.e. opportunities).
8. Identify potential for cumulative effects, if possible, and non-climate related stressors that may be more important.
9. Finalize with discussion of uncertainty, likelihood of occurrence and confidence in inferences.

This study has therefore attempted to cover the following aspects:

- Developing an understanding of approaches to I&V analysis.
- Developing information on climate change stressors and their potential, impacts.
- Understanding the species at risk that need to be looked at.
- Developing a list of the stressors that need to be considered and the relative extent of exposure for these organisms.
- Evaluating the sensitivity of the organisms to climate change.
- Identifying potential impacts that affect species at risk in Canada
- Assessing the relative vulnerability of the species based on 10-year and 50-year scenario changes.

The purpose of any climate adaptation I&V assessments is to assess and prioritize risks posed to individual components of socio-ecological systems so as to assist with the development of response strategies and programs (Fuessell and Klein 2006). However efforts towards this objective are always complicated by uncertainty about the rate, intensity, and likelihood of change and resultant impacts, particularly where the systems being assessed are poorly understood (Jones 2000). I&V analyses can only be as sophisticated and meaningful as the information and assumptions on which they are based (Chin *et al.* 2010). As will be appreciated, because of the wide dimensions and characteristics of the Atlantic Basin, the number and variety of the species at risk that are involved, as well as numerous climate change stressors and their potential direct and indirect impacts, it has not been possible within the timeframe of this study to conduct any detailed or sophisticated I&V analysis. However, it has been possible to review and identify aspects that pose potential risks to these species, as well as their ability to adapt to climate change related stressors.

It was considered important to present a short front section that provides relevant background material and context to I&V analysis and the methodological complexities involved. This is done as it provides rationale to the approach that has been taken by this study. It is accepted that it might lack detail and/or omit specific facts that some parties might wish to see. However, it is assumed that additional detail will appear in other contributions that are concurrently being prepared by other ACCASP contributors. The topics covered in this section include:

- Impacts and vulnerability analysis
- Broad characteristics of the Atlantic Basin
- Climate change stressors and impacts on the aquatic environment
- Species at Risk

8.2.3 Impacts and Vulnerability Analysis

Vulnerability analyses are concerned with assessing the degree to which systems (organisms) are susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes (Fuessel and Klein 2006). For the purposes of this report it is pertinent to present a framework described by Fuessel and Klein (2006), as it provides an overall picture of the chief elements of I&V analysis and how this connects to climate change management and policy (Fig. 8–1).

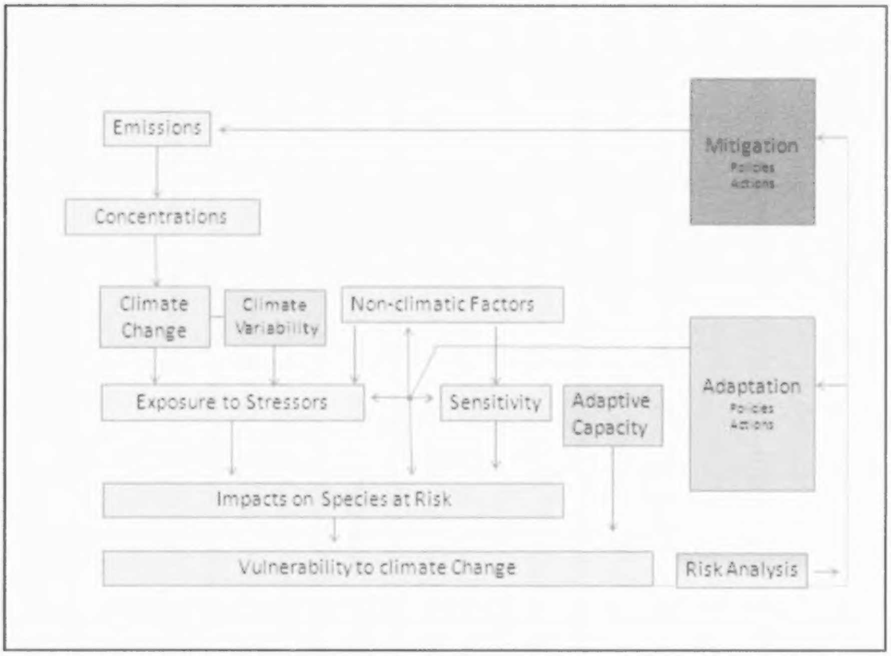
Emissions
Mitigation
Policies
Actions
Concentrations
Climate Change
Climate Variability
Non-climatic Factors
Exposure to Stressors
Sensitivity
Adaptive Capacity
Adaptation
Policies
Actions
Impacts on Species at Risk
Vulnerability to climate Change
Risk Analysis

Figure 8–1 Framework illustrating the elements of I&V analysis and how they are linked in risk analysis (adapted from Fuessel and Klein 2006).

Based on the above model, the main elements of an I&V analysis include:

1. A description of the ***target area and entities*** to be assessed. For the purposes of this screening study it was felt important to focus on only simple basics of the target area and not become too involved in the detailed spatial variation within the system.
2. Identification and quantitative description of the ***climate change stressors*** that are of interest. This includes a description of the trends, projections, and variability for stressors based on selected climate change scenarios. In many cases most I&V analyses involve an assessment as to whether there is concrete evidence as to whether there is change taking place and if any specific stressor might have a potential impact. The description ideally includes definition of future climate change scenarios that apply, scaled to the appropriate spatial and temporal scale. As will be noted for some of the Canadian species at risk (migratory species) there are key climate change stressors external to the Atlantic Basin.
3. An assessment of the ***exposure*** of the target species to these stressors. Exposure is related to the dosage-time-frequency to which the target system or organism is exposed to a stressor. In most cases exposure is related to the habitat and the time frequency that the organism occupies the habitat.

4. An assessment of the ***sensitivity*** of target species to the stressors. Sensitivity is defined as "The degree to which a system is affected, either adversely or beneficially by climate- related stimuli". Ideally this aspect has to take into account both direct and indirect stressors. Life cycle stages are important in influencing sensitivity (Portner and Peck 2010), but this study has not gone into any detail on this aspect.
5. An assessment of potential impacts on the target (species, habitat, system). Although there are many potential impacts (see section 2.4), for species at risk it is largely a question of assessing the potential impact on populations of adult organisms and on their distribution (COSEWIC 2012).
6. An assessment of of the ***adaptive capacity (resilience)*** of the target species. Adaptive capacity is defined as "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences".
7. Integrating information to provide an assessment of overall ***vulnerability*** of the target species to climate change. Vulnerability is defined as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity and its adaptive capacity".

There have been numerous climate change I&V assessments carried out for the marine environment. These have covered a wide range of topics ranging from the global marine environment (e.g. Cochrane *et al.* 2009), eco-regions (e.g. the North East Atlantic - West Coast Energy Ltd 2005; Australia – Pecl *et al.* 2011), to specific sites and species (e.g.Sharks and the Great Barrier Reef - Chin *et al.* 2010; Arctic marine mammals - Laidre *et al.* 2008; cetaceans – MacLeod 2009). Although the detail, approaches and methods that have been used have varied considerably, most have focused on attempting to describe as far as is possible the qualitative and/or quantitative dimensions of relevant I&V components. A review of the literature indicates that there is no universally accepted standard quantitative method on how to perform a climate change I&V analysis. This is not surprising in view of the numerous direct and indirect stressors, species, habitats and scenarios that need to be covered. Most analyses have involved hypothetical, semi-quantitive expert judgement-based approaches (see MacLeod 2009; Chin *et al.* 2010) or predictive modelling (see Cheung *et al.* 2009). In each case there have usually been numerous assumptions made that apply specifically to the particular I&V analysis that has been carried out, and which are not necessarily directly transferable to other systems or species. This study has only been able to cover the rudimentary elements of an I&V analysis and it should be accepted that the situation is far more complex than depicted.

8.2.4 Characteristics of the Atlantic Basin

The target area for this study (Atlantic Basin) includes the overall marine area that is covered by four of the DFO administrative regions, notably:

- Quebec - covering an area extending from the freshwater outflows from the Great Lakes, the estuarine part of the St Lawrence River beyond Il D'Orleans, and the oceanic part of the Gulf of St Lawrence (GoSL).
- Gulf - including that part of the Gulf of St Lawrence adjacen to New Brunswick, and the Northumberland Strait south of PEI through to Cape Breton Isle.
- Maritimes – including the Scotian Shelf, the Canadian portion of the Gulf of Maine (GOM) and the Bay of Fundy (BoF).
- Newfoundland and Labrador – including a wide area of continental shelf surrounding Newfoundland (the Gulf of St Lawrence, Labrador Sea and Western Atlantic) and some 2.900 km of coastline stretching as far north as the Torngat Mountains National Park.

The latitude and longitude of the target area essentially lies between latitudes of 40-60 °N, and between longitudes of 46-70 °W. The area contains three biogeographic marine areas as classified by DFO (2009), notably the Scotian Shelf, the Newfoundland Labrador Shelves, and the Gulf of St Lawrence. More biogeographic details are available in Chapter 1 of this report.

8.2.5 Climate Change Stressors and Impacts on the Aquatic Environment

Over the last decade there have been numerous reviews of climate change stressors and their potential impacts on the marine environment (see: IPCC 2007; Hobday *et al.* 2007; Perry 2011; Koehn *et al.* 2011; Cochrane *et al.* 2009; Shackell and Loder 2012). As the species at risk covered by this analysis occupy a wide range of freshwater, estuarine and marine habitats within, and outside of, the Canadian Atlantic Basin it is pertinent to provide a stressor/impact summary that covers the relevant range of habitats in which they occur (Table 8–1).

Table 8–1 Some climate-related threats and potential consequences to aquatic ecosystems based on spatial considerations (adapted from Perry 2011; and Koehn *et al.* 2011)

Spatial System	Climate-related stressor	Potential Impact
Lakes and reservoirs	Increased/decreased inflow	Habitat loss
	Increased water temperature	Reduced connectivity
	Droughts and floods	Physical damage
	Deoxygenation	Altered productivity
Rivers	Increased/decreased flow	Habitat loss
	Increased temperature	Temperature extremes
		Increased variability
		Reduced connectivity
		Changed material tranport
Coastal		
Estuaries and saltmarshes	Sea level rise	Salinity changes
	Rising temperature	Habitat loss

Spatial System	Climate-related stressor	Potential Impact
	Increased/decreased flow of both marine and freshwater	Reduced connectivity Physical damage Altered productivity
Beaches	Sea level rise Storm surge Increasing storm frequency and intensity	Coastal erosion Loss of habitat Altered zonation
Rocky substrates Intertidal	Sea level rise Storm surge Increasing storm frequency and intensity	Altered zonation Changes in exposure
Kelp forests Coral reefs	Rising temperatures Sea level rise Altered circulation	Changes in growth and distribution Reduced calcification Disrupted larval transport and connectivity
Oceanic Systems		
Pelagic	Rising temperatures Rising atmospheric carbon dioxide Increased acidity Altered circulation and upwelling Decreased oxygen concentrations	Changes in species distributions and timing of events, Increased primary production Reduced calcification Changes in nutrient inputs Expanded anoxic zones
Polar	Rising temperatures Ice reduction	Sea ice loss Increased primary production Loss of habitat Circulation changes
Deep sea	Rising temperatures Decreased oxygen Increased acidity	Increased stratification Decreased nutrient inputs Species distribution and composition shifts Reduced calcification Increased anoxic zones

It is recognized that there are many potential climate-related stressors, each of which can impact separately, indirectly, and/ or cumulatively on habitats and organisms. Based on an analysis of identified potential impacts on fish in Australia Koehn *et al.* (2011) conclude that *"climate change will have a range of direct effects on the physiology, fitness, and survivorship of marine, estuarine and freshwater fishes, as well as indirect effects via habitat degradation and changes to ecosystems. Effects will differ across populations, species and ecosystems with some impacts being complex and causing unexpected outcomes".* The same statement is also applicable to other groups of organisms such as mammals (Kovacs and Lydersen 2008; Moore and Huntington 2008), reptiles (Hawkes *et al.* 2009) and molluscs (Cheung *et al.* 2009).

From a climate change impact perspective it is probably most convenient to separate impacts into primary, secondary and tertiary categories (Koehn *et al.* 2011). Primary impacts are climate-related changes that directly affect the behaviour, physiology, fitness and survivorship via a one step process. Secondary impacts relate to changes in the quality or quantity of habitats available to the species, whilst tertiary impacts are those that occur as a result of several factors or involve multiple pathways of effects (Balcombe *et al.* 2011). Direct and indirect impacts may affect different species and life stages differently.

8.2.6 Changes in Climate Change Stressors over the Atlantic Basin Area

As part of ACCASP, a Trends and Projections (T&P) task team has been active in reviewing and assessing information on selected climate change variables that might represent stressors to ecosystems and species of interest to the DFO. This has been geared towards providing information on 1) historical spatial and temporal trends which provide information on the current rate of change; 2) expected changes in the forthcoming decade; and 3) expected changes on a 50-year period. It should be recognized that scenario projection analyses, and their values, are continually changing as researchers make progress. Therefore the values presented should be seen as being best-estimates given at the time of dissemination. Oceanographic trends and projections for the region used to build the assessment herein are summarized in Chapter 1 and gleaned from reports listed in Appendix.

At the stage of writing this current chapter, the T&P group could only provide qualitative values for many of the variables because observed and/or predicted rates of change are masked by high spatial and temporal variability across the target area (Trends and Projections Working Group 2012). From an I&V perspective, and the information available, it can be concluded that almost all of the variables will exhibit changes and the trends have been identified. The most appropriate variable to focus on (with the best quantitative prediction) is that of water temperature where a 50-year general increase of 1-5°C is anticipated.

8.2.7 Species at Risk

In Canada, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), under its mandate from the Species at Risk Act (SARA), provides the main mechanism by which species at risk are assessed and designated according to their degree of endangerment. The purpose of the SARA is to prevent wildlife species from becoming extinct or extirpated; help in the recovery of extirpated, endangered or threatened species; and ensure that species of special concern do not become endangered or threatened. COSEWIC evaluates the status of the country's wildlife and assigns particular risk categories to species (http://www.cosewic.gc.ca/eng/sct3/index_e.cfm). These include:

- Extinct - a species that no longer exists.
- Extirpated - a species no longer existing in the wild in Canada, but occurs elsewhere.
- Endangered - a species facing imminent extirpation or extinction.
- Threatened - a species likely to become endangered if limiting factors are not reversed.
- Special concern - a species that may become a threatened or an endangered species because of a combination of biological characteristics and identified threats.
- Candidate species – those species which are recognized by COSEWIC as being species which merit investigation and assessment through the COSEWIC process.

The attributes that are used by COSEWIC to assess and judge the status of a species include (http://www.cosewic.gc.ca/eng/sct0/assessment_process_e.cfm#tbl2):

1. Decline in total number of mature individuals
2. Small distribution range and a decline or fluctuation in range
3. Small and declining number of mature individuals
4. Very small or restricted total population
5. Quantitative analysis showing high probability of extinction.

Although many species receive attention from COSEWIC, it requires formal federal government ratification before any species becomes legally protected under SARA, and receives mandatory management attention from DFO.

Each of the above attributes has associated quantitative criteria that are used in assessing the status of the species. From a I&V perspective these attributes provide a guide to the type of feedback that the analysis should attempt to generate - notably, providing information about to the extent that climate change, and its associated stressors, impact on COSEWIC attributes and criteria.

8.3 SPECIES AT RISK IN THE ATLANTIC BASIN

Because this study was concerned with assessing risks and scenarios for species at risk, it was felt that it should not just focus on those species that are protected under SARA, but also include those species that had received, or were receiving, attention from COSEWIC. For practical purposes, it was therefore decided to screen for those species that were listed in the Canadian Species at Risk Registry as being either threatened, endangered, special concern, or a candidate species for assessment (http://www.sararegistry.gc.ca/default_e.cfm). It was also decided not to include species that were listed as being either "extinct", "extirpated", or "not at risk". The range selector for the database search was the "Atlantic Ocean" area of Canada (including Quebec, Nova Scotia, Newfoundland and Labrador, and New Brunswick), and species groups (fish, mammals, reptiles, molluscs - freshwater and marine). The COSEWIC list of candidate species was also consulted (http://www.cosewic.gc.ca/eng/sct3/index_e.cfm). Decision on this approach was done following consultation with the Maritimes Species at Risk Office (Marcia Penney and Andrea Carew, Species at Risk Division, Maritimes).

A listing of relevant species that have received attention from, or are of current interest to, COSEWIC is included in Table 8–2. The list was obtained from the Species at Risk Public Registry (http://www.sararegistry.gc.ca/default_e.cfm) and amounted to 52 species from the COSEWIC taxon groups fish (marine and freshwater), mammals, reptiles and molluscs. From an I&V perspective it was felt that these would be best separated into separate groups based on their taxa and the predominant habitats that they occupy. The assumptions being that firstly, the different taxa respond differently to climate change stressors; and secondly that exposure to climate change stressors will depend on the habitats that they occupy. The different habitat grouping is particularly relevant to the fish where three basic habitat groupings have been selected (pelagic, demersal-benthic, and diadramous). The rationale is that the three groups represent different habitat types in terms of the types of stressors and the exposure levels that species experience. A schematic of the groupings is presented in Figure 8–2, which indicates that the analysis includes:

- 33 species of fish, of which;
- 7 are pelagic
- 19 are demersal-benthic
- 7 are diadramous

It is accepted that both pelagic and demersal species migrate vertically between layers, but assignment was based on the habitat where their occurrence predominates.

- 10 cetaceans
- 4 pinnipeds
- 3 reptiles
- 1 mollusc
- 15 species that are candidate species under consideration for assessment by COSEWIC

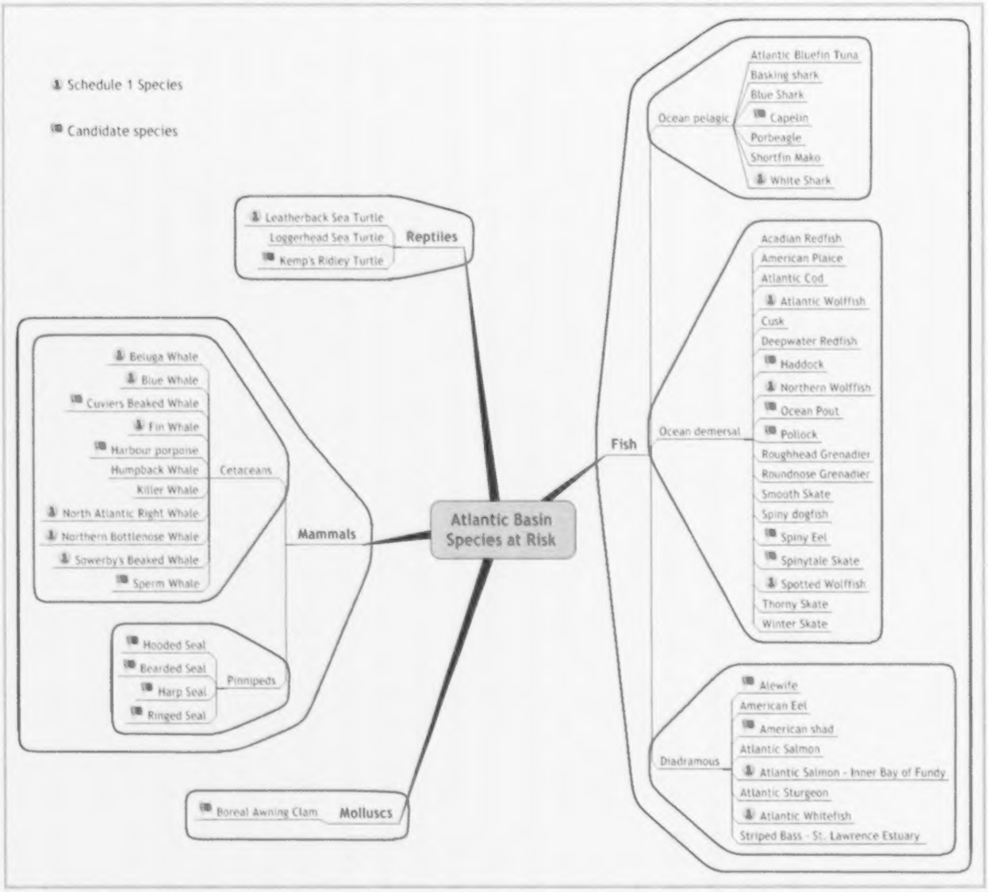
♟ Schedule 1 Species
⚑ Candidate species
♟ Leatherback Sea Turtle
Loggerhead Sea Turtle
⚑ Kemp's Ridley Turtle
Reptiles
♟ Beluga Whale
♟ Blue Whale
⚑ Cuviers Beaked Whale
♟ Fin Whale
⚑ Harbour porpoise
Humpback Whale
Killer Whale
♟ North Atlantic Right Whale
♟ Northern Bottlenose Whale
♟ Sowerby's Beaked Whale
⚑ Sperm Whale
Cetaceans
⚑ Hooded Seal
⚑ Bearded Seal
⚑ Harp Seal
⚑ Ringed Seal
Pinnipeds
Mammals
⚑ Boreal Awning Clam
Molluscs
Atlantic Basin Species at Risk
Fish
Ocean pelagic
Atlantic Bluefin Tuna
Basking shark
Blue Shark
⚑ Capelin
Porbeagle
Shortfin Mako
♟ White Shark
Ocean demersal
Acadian Redfish
American Plaice
Atlantic Cod
♟ Atlantic Wolffish
Cusk
Deepwater Redfish
⚑ Haddock
♟ Northern Wolffish
⚑ Ocean Pout
⚑ Pollock
Roughhead Grenadier
Roundnose Grenadier
Smooth Skate
Spiny dogfish
⚑ Spiny Eel
⚑ Spinytale Skate
♟ Spotted Wolffish
Thorny Skate
Winter Skate
Diadramous
⚑ Alewife
American Eel
⚑ American shad
Atlantic Salmon
♟ Atlantic Salmon - Inner Bay of Fundy
Atlantic Sturgeon
♟ Atlantic Whitefish
Striped Bass - St. Lawrence Estuary

Figure 8–2 Marine species at risk in the Atlantic Basin target area. The following is an excerpt from: **http://www.dfo-mpo.gc.ca/species-especes/faq/faq-eng.htm.** "Schedule 1 of the Species at Risk Act is the official list of wildlife species at risk in Canada. It includes species that are extirpated (extinct in Canada), endangered, threatened, and of special concern. Once a species is listed on Schedule 1, protection and recovery measures are developed and implemented. Species that were designated at risk by COSEWIC (the Committee on the Status of Endangered Wildlife in Canada) before the creation of the Species at Risk Act must be reassessed according to the new criteria of the Act before they can be added to Schedule 1. These species are listed on Schedules 2 and 3, and are not yet officially protected under SARA. Once the species on Schedules 2 and 3 have been reassessed, the Schedules themselves will be eliminated, and species will simply be listed or not listed under the Act."

Table 8–2 List of species at risk for the Atlantic Basin—accessed from the Canadian Species at Risk Registry on 24th July 2012. (NS = No status).

Common Name	Scientific Name	COSEWIC Status	SARA Status	Schedule
Fishes				
Pelagic-open ocean				
Atlantic Bluefin Tuna	*Thunnus thynnus*	Endangered	NS	
Basking Shark	*Cetorhinus maximus*	Special concern	NS	
Blue Shark	*Prionace glauca*	Special concern	NS	
Capelin	*Mallotus villosus*	Candidate	NS	
Porbeagle	*Lamna nasus*	Endangered	NS	
Shortfin Mako	*Isurus oxyrinchus*	Threatened	NS	
White Shark	*Carcharodon carcharias*	Endangered	Endangered	1
Demersal/benthic				
Acadian Redfish	*Sebastes fasciatus*	Threatened	NS	
American Plaice	*Hippoglossoides platessoides*	Threatened	NS	
Atlantic Cod	*Gadus morhua*	Endangered	NS	3
Atlantic Wolffish	*Anarhichas lupus*	Special concern	Special concern	1
Cusk	*Brosme brosme*	Threatened	NS	
Deepwater Redfish (2 populations)	*Sebastes mentella*	Threatened-endangered	NS	
Haddock	*Melanogrammus aeglefinus*	Candidate	NS	
Northern Wolffish	*Anarhichas denticulatus*	Threatened	Threatened	1
Ocean Pout	*Zoarces americanus*	Candidate	NS	
Pollock	*Pollachius virens*	Candidate	NS	
Roughhead Grenadier	*Macrourus berglax*	Special concern	NS	
Roundnose Grenadier	*Coryphaenoides rupestris*	Endangered	NS	
Smooth skate	*Malacoraja senta*	Special concern-	NS	
Spiny dogfish	*Squalus acanthias*	Special concern	NS	
Spiny Eel	*Notacanthus chemnitzi*	Candidate	NS	
Spinytail skate	*Bathyraja spinicauda*	Candidate	NS	
Spotted Wolffish	*Anarhichas minor*	Threatened	Threatened	1
Thorny skate	*Amblyraja radiata*	Special concern	NS	
Winter Skate (several populations)	*Leucoraja ocellata*	Threatened-endangered-special concern	NS	

Common Name	Scientific Name	COSEWIC Status	SARA Status	Schedule
Diadramous				
Alewife	*Alosa pseudoharengus*	Candidate	NS	
American Eel	*Anguilla rostrata*	Threatened	NS	
American shad	*Alosa sapidissima*	Candidate		
Atlantic Salmon (various populations)	*Salmo salar*	Threatened-special concern-endangered	NS	
Atlantic Salmon (Inner Bay of Fundy)	*Salmo salar*	Endangered	Endangered	1
Atlantic Sturgeon	*Acipenser oxyrinchus*	Threatened	NS	
Atlantic Whitefish	*Coregonus huntsman*	Endangered	Endangered	1
Striped Bass St. Lawrence Estuary population	*Morone saxatilis*	Threatened	NS	
Mammals				
Cetaceans				
Beluga Whale (2 populations)	*Delphinapterus leucas*	Threatened-endangered	Threatened	1
Blue Whale	*Balaenoptera musculus*	Endangered	Endangered	1
Cuviers Beaked Whale	*Ziphius cavirostris*	Candidate		
Fin Whale	*Balaenoptera physalus*	Special concern	Special concern	1
Harbour porpoise	*Phocoena phocoena*	Special concern	Threatened	2
Humpback Whale	*Megaptera novaeangliae*	Not at risk	Special concern	3
Killer Whale	*Orcinus orca*	Special concern	NS	
North Atlantic Right Whale	*Eubalaena glacialis*	Endangered	endangered	1
Northern Bottlenose Whale (2 populations)	*Hyperoodon ampullatus*	Endangered	Endangered	1
Sowerby's Beaked Whale	*Mesoplodon bidens*	Special concern	Special concern	1
Sperm Whale	*Physeter macrocephalus*	Candidate		
Pinnipeds				
Bearded Seal	*Erignathus barbatus*	Candidate	NS	
Harp Seal	*Phoca groenlandica*	Candidate	NS	
Hooded Seal	*Cystophora cristata*	Candidate	NS	
Ringed seal	*Pusa hispida hispida*	Candidate	NS	

Common Name	Scientific Name	COSEWIC Status	SARA Status	Schedule
Reptiles				
Leatherback Sea Turtle	*Dermochelys coriacea*	Endangered	Endangered	1
Loggerhead Sea Turtle	*Caretta caretta*	Endangered	NS	
Kemp's Ridley sea turtle	*Lepidochelys kempii*	Candidate	NS	
Mollusc				
Boreal Awning Clam	*Solemya borealis*	Candidate	NS	

8.4 EXPOSURE ANALYSIS

Key stressors included: temperature (surface and bottom), salinity (surface), density stratification, sea ice, water mass characteristics (e.g., relative proportions of freshwater, brackish, and salt waters), boundary current indices, waves/sea level, dissolved oxygen, pH, nutrients, and sedimentation. For the purpose of this screening level analysis it was felt that it would be appropriate to provide a semi-quantitive indication of the general exposure that the selected SAR groups experience from a broader suite of climate change stressors. This is because of the wide range of habitats that are occupied by the 52 listed species, and the likelihood that other stressors might play an important role. Information on stressors was derived through various workshops and from John Loder's trends and projections team (DFO, Maritimes) which resulted in many trends and projections reports (see Appendix 1 of the main report and Hebert et al 2012).

For each group it was decided to assign a ranking level to the general exposure that the groups might be expected to experience within the habitats that they occupy. The ranking is a subjective one done by this author and based on anticipated exposure of the group to each of the stressors over the geographic range of the Atlantic Basin. It is an attempt to relate the overlap between the species geographic range and habitat usage with the predicted footprint of the climate change factor. The ranking levels assigned were zero, low, medium and high, which also correspond with numeric values respectively of 0, 1, 2 and 3. Using the simple assumption of equal weighting to these stressors, and totalling the values, it is also possible to obtain an integrated value for overall exposure by each of the groups. Ideally it is recommended that such an analysis be done by a panel of experts as such analyses generate considerable differences in opinion (Teck *et al.* 2010). This is perhaps an aspect for follow up by the DFO. The exposure ratings generated by this study would benefit through refinement by a broader corps of scientists and resource managers.

8.4.1 Fish

8.4.1.1 Pelagic

Pelagic species occupy the surface layer levels of the ocean that is exposed to greater fluctuations and changes in water temperature. A profile of the exposure of this group (Table 8–3) to the suite of climate change stressors indicates an integrated numeric exposure rating of 22 (sum of all ratings). The climate change stressor assigned the highest exposure rating is surface water temperature.

Table 8–3 Profile of climate change stressor exposure ratings for pelagic species in the Atlantic Basin.

Climate Change Variable	Zero	Low	Medium	High
Annual mean air temperature			2	
Precipitation	0			
Winds and storms		1		
Sea ice		1		
Lake and river flow		1		
Ice cover in rivers	0			
Sea surface temperature				3
Sub-surface temperature			2	
Salinity			2	
Stratification			2	
Circulation		1		
Mean sea level	0			
Extreme sea level	0			
Waves		1		
Coastal erosion and flooding		1		
Dissolved oxygen/hypoxia			2	
Acidity		1		
Nutrients (N,P,Si)			2	

8.4.1.2 Demersal-benthic

Demersal-benthic species occupy waters mainly of the continental shelf area that are generally colder, and which are influenced more by thermal stratification. The integrated exposure total is 22, which is the same as that of the pelagic species. Subsurface temperature and dissolved oxygen are the potential high exposure stressors (Table 8–4).

Table 8–4 Profile of climate change stressor exposure ratings for demersal-benthic species in the Atlantic Basin.

Climate Change Variable	Zero	Low	Medium	High
Annual mean air temperature		1		
Precipitation	0			
Winds and storms	0			
Sea ice		1		

Climate Change Variable	Zero	Low	Medium	High
Lake and river flow		1		
Ice cover in rivers	0			
Sea surface temperature			2	
Sub-surface temperature				3
Salinity			2	
Stratification			2	
Circulation			2	
Mean sea level	0			
Extreme sea level	0			
Waves	0			
Coastal erosion and flooding		1		
Dissolved oxygen/hypoxia				3
Acidity			2	
Nutrients (N,P,Si)			2	

8.4.1.3 Diadramous

Diadramous species spend parts of their life cycles in both the marine and freshwater environments. As such they are exposed to a wider variety of habitats ranging from the ocean, to coastal (estuaries) and inland systems (rivers and lakes). The integrated exposure total is **40** reflecting the fact that diadramous species are exposed to a wider range of climate change stressors than the pelagic and demersal-benthic groups. The high exposure stressors include: dissolved oxygen, lake and river flow, ice cover in rivers, river temperature, and ocean surface temperature (Table 8–5).

Table 8–5 Profile of climate change stressor exposure ratings for diadramous species in the Atlantic Basin.

Climate Change Variable	Zero	Low	Medium	High
Annual mean air temperature			2	
Precipitation			2	
Winds and storms			2	
Sea ice		1		
Lake and river flow				3
Ice cover in rivers				3
River temperature				3
Sea surface temperature				3
Sub-surface temperature			2	
Salinity			2	
Stratification			2	

Climate Change Variable	Zero	Low	Medium	High
Circulation			2	
Mean sea level		1		
Extreme sea level		1		
Waves			2	
Coastal erosion and flooding			2	
Dissolved oxygen/hypoxia				3
Acidity			2	
Nutrients (N,P,Si)			2	

8.4.2 Mammals

8.4.2.1 Cetaceans

The cetaceans in the Atlantic Basin are essentially pelagic with a wide distribution range. The integrated exposure rating is 19 with sea surface temperature being the most important climate change stressor (Table 8–6).

Table 8–6 Profile of climate change stressor exposure ratings exposure ratings for cetaceans in the Atlantic Basin.

Climate Change Variable	Zero	Low	Medium	High
Annual mean air temperature			2	
Precipitation		1		
Winds and storms			2	
Sea ice			2	
Lake and river flow	0			
Ice cover in rivers	0			
River temperature	0			
Sea surface temperature				3
Sub-surface temperature			2	
Salinity		1		
Stratification			2	
Circulation			2	
Mean sea level	0			
Extreme sea level	0			
Waves		0		
Coastal erosion and flooding	0			
Dissolved oxygen/hypoxia		0		
Acidity		0		
Nutrients (N,P,Si)			2	

8.4.2.2 Pinnipeds

Pinnipeds (seals) occupy both terrestrial and aquatic habitats and are also highly dependent on sea ice as part of their general habitat occupancy and breeding. The integrated value is **32** with air temperature, winds and storms, and sea ice having high exposure ratings (Table 8–7).

Table 8–7 Profile of climate change stressor exposure ratings for pinniped species in the Atlantic Basin

Climate Change Variable	Zero	Low	Medium	High
Annual mean air temperature				3
Precipitation			2	
Winds and storms				3
Sea ice				3
Lake and river flow	0			
Ice cover in rivers	0			
River temperature	0			
Sea surface temperature			2	
Sub-surface temperature			2	
Salinity		1		
Stratification			2	
Circulation			2	
Mean sea level			2	
Extreme sea level			2	
Waves			2	
Coastal erosion and flooding			2	
Dissolved oxygen/hypoxia		1		
Acidity		1		
Nutrients (N,P,Si)			2	

8.4.3 Reptiles

The reptiles in the group are essentially pelagic, but are highly dependent for land habitat as part of their breeding requirements. Although the land habitats are not in Canada the exposure rating has included consideration of this aspect. The integrated exposure value is **39** with air temperature, precipitation, winds and storms, sea level, waves, coastal erosion, and sea surface temperature being allocated high exposure ratings (Table 8–8).

Table 8–8 Profile of climate change stressor exposure ratings for reptiles in the Atlantic Basin.

Climate Change Variable	Zero	Low	Medium	High
Annual mean air temperature				3
Precipitation				3
Winds and storms				3
Sea ice		1		
Lake and river flow			2	
Ice cover in rivers	0			
River temperature		1		
Sea surface temperature				3
Sub-surface temperature			2	
Salinity		1		
Stratification			2	
Circulation			2	
Mean sea level				3
Extreme sea level				3
Waves				3
Coastal erosion and flooding				3
Dissolved oxygen/hypoxia		1		
Acidity		1		
Nutrients (N,P,Si)			2	

8.4.4 Molluscs

The only mollusc of concern to this study (the boreal awning clam) is typically found in shallow water in the intertidal zone at the water's edge. The integrated exposure value is **31** with surface temperature, mean sea level, extreme sea level, waves, coastal erosion and flooding, and acidity being the identified high exposure stressors (Table 8–9).

Table 8–9 Profile of exposure ratings for mollusc species to climate change stressors in the Atlantic Basin.

Climate Change Variable	Zero	Low	Medium	High
Annual mean air temperature		1		
Precipitation		1		
Winds and storms			2	
Sea ice	0			
Lake and river flow			1	
Ice cover in rivers	0			

Climate Change Variable	Zero	Low	Medium	High
River temperature	0			
Sea surface temperature				3
Sub-surface temperature	0			
Salinity		1		
Stratification		1		
Circulation			2	
Mean sea level				3
Extreme sea level				3
Waves				3
Coastal erosion and flooding				3
Dissolved oxygen/hypoxia			2	
Acidity				3
Nutrients (N,P,Si)			2	

8.5 ANALYSIS OF SENSITIVITY

There are many indicators that have been used to assess sensitivity of a species to climate change (see Box 1).

Box 1

Examples of indicators that reflect sensitivity to climate change (from Schlesinger et al. 2011)

Dispersal and movements
Predicted sensitivity to changes in temperature
Predicted sensitivity to changes in precipitation, hydrology, or moisture regime
Dependence on a specific disturbance regime likely to be impacted by climate change
Dependence on ice, ice-edge, or snow-cover habitats
Restriction to uncommon geological features or derivatives
Dependence on other species to generate habitat
Dietary versatility
Measured genetic variation
Occurrence of bottlenecks in recent evolutionary history
Phenological response to changing seasonal temperature and precipitation dynamics

As it was not considered feasible to do a detailed comprehensive analysis of each of the factors for all of the 52 species, it was decided to use the factor(s) that was most appropriate to the groups (fish, mammals, reptiles). Water temperature is considered to be the key climate change variable that impacts on marine organisms as it directly affects physiological condition, development growth rates, reproduction, and behaviour (Portner and Peck 2010). Evolutionary theory contends that most organisms on Earth have adapted over time to survive within a range of temperatures and to tolerate varied temperature-imposed habitat conditions. It is therefore not surprising that temperature is the key variable that determines the distribution and habitat preferences of most marine organisms (Cheung *et al.* 2009), and is the one that is most often used in analyses to assess the sensitivity of species. It was therefore felt appropriate that sensitivity to water temperature change would be the most useful primary indicator to use as a screen for sensitivity to climate change. However, where other factors are observed to be more important for any of the groups these would have to be taken into consideration. This was also supported by the fact that the Trends and Projections Working Group had provided a quantitative prediction of the anticipated 50-year change in general water temperature over the Atlantic Basin.

A survey was done of the literature to obtain water temperature preference characteristics for each of the 52 species with the objective to obtain a profile that gives an indication of the water temperature ranges in which each of the species occurs, as well the favoured temperatures. The temperature range information was obtained from:

- Scans of COSEWIC/DFO species reports that are publically available from the Species at Risk Public Registry (http://www.sararegistry.gc.ca/sar/index/default_e.cfm0). Because of their large number, these reports are not individually cited in the reference list to this report.
- Data and information available on species from Fishbase (see Froese and Pauly 2012 -http://www.fishbase.org/search.php).
- Literature for the Atlantic area and elsewhere that had useful or authoritative information on any of the species (e.g., Scott 1982; Scott and Scott 1988; Campana and Joyce 2009; MacLeod 2009).

8.5.1 Fish

Profiles of the temperature ranges for each of the fish species are presented in Table 8–10. It should be noted that information was obtained from the sources cited above, and there may be different values obtained from other sources. There is therefore room for refinement of these profiles. Here we only estimate whether SAR are sensitive at the lower end of the anticipated temperature range in 50 years. It is highly recommended that a more detailed follow up study be undertaken of the temperature preferences of these species, as well as the approach to estimating upper and lower sensitivity values. The analysis does however serve to indicate the preferences of the groups in terms of their thermal requirements and the relative sensitivities of the fish species to water tenmperature increases in the Atlantic Basin. For the fish species a quick index of sensitivity has been derived by calculating a factor (S) from the formula:

$S = C/R$

Where,

C = number of degrees centigrade in which the species is found in the 0-3 degree range, a value that corresponds to the anticipated 50-year climate change general warming change at the cold end of the temperature range in the Atlantic Basin. In the case of this study it was considered that changes at the colder end of each species range was more important than changes at the upper end. Based on the profiles obtained it is highly unlikely that the predicted temperature change will affect the upper limits of tolerance for the species concerned.

R = the range of temperature for the organism.

Sensitivity rating was assigned 1, 2 or 3 based on the factor value where < 0.1 is low sensitivity and represents less than 10% of the organism's temperature range (1); 0.1- 0.3 is intermediate sensitivity (2); and > 0.3 is a high sensitivity representing more than 30% of the organism's temperature range (3). The analysis indicates that pelagic and diadramous fish species have relatively low sensitivity to temperature change whilst all the demersal-benthic species have intermediate to high sensitivity. For the pelagic species, exceptions were Capelin and the Porbeagle Shark. It is interesting to note that the Porbeagle Shark is described as one of the most cold-tolerant of the pelagic sharks (Campana and Joyce 2004). Similarly Capelin has been described as a "canary of climate change" because of its sensitivity and response to temperature changes (Rose 2005). Of the demersal-benthic species the most sensitive (with factor values > 0.4) appear to be the Northern Wolffish, Spotted Wolffish, Roughhead Grenadier and the Spiny Eel. This overall pattern is consistent with the geographical and habitat distribution of the species and the thesis that marine fish have evolved to adapt to a geographic and morphometric range based on sensitivity and tolerance to temperature (Portner and Peck 2012).

Table 8–10 Temperature ranges for fish species at risk in the Atlantic Basin. Range of temperature and sensitivity rating is given (1= low sensitivity, 2 = intermediate sensitivity, and 3 = high sensitivity). Shaded areas represent preferred temperature range where information was available (for some species this was not available).

			Temperature in degree Celsius																														Range	0-3	Factor S	Rating
Species		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30				
Pelagic species																																				
Atlantic Bluefin Tuna					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			25	1	0.04	1
Basking Shark								x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x							19	0	0.00	1
Blue Shark							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x											16	0	0.00	1
Capelin	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																	16	5	0.31	3
Porbeagle			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x													18	3	0.17	2
White Shark							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				23	0	0.00	1
Demersal-benthic																																				
Acadian Redfish		x	x	x	x	x	x	x	x	x	x	x	x	x	x																		14	4	0.29	3
American Plaice		x	x	x	x	x	x	x	x	x	x	x	x	x	x																		14	4	0.29	3
Atlantic Cod		x	x	x	x	x	x	x	x	x	x	x	x	x	x																		14	4	0.29	3
Atlantic Wolffish	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																		15	5	0.33	3
Cusk				x	x	x	x	x	x	x	x	x	x	x																			11	2	0.18	2
Deepwater Redfish		x	x	x	x	x	x	x	x	x	x	x	x																				12	4	0.33	3
Haddock			x	x	x	x	x	x	x	x	x	x	x	x	x																		13	3	0.23	2
Northern Wolffish	x	x	x	x	x	x	x	x	x	x	x	x																					12	5	0.42	3
Ocean Pout		x	x	x	x	x	x	x	x	x	x	x	x																				12	4	0.33	3
Pollock				x	x	x	x	x	x	x	x	x	x	x																			11	2	0.18	2
Roughhead Grenadier			x	x	x	x	x																										5	3	0.60	3
Roundnose Grenadier				x	x	x	x	x																									5	2	0.40	2
Smooth Skate		x	x	x	x	x	x	x	x	x	x	x	x	x	x																		14	4	0.29	2
Spiny dogfish					x	x	x	x	x	x	x	x	x																				9	0	0.00	2
Spiny Eel				x	x	x																											3	2	0.67	3
Spinytail skate			x	x	x	x	x	x	x	x																							8	3	0.38	3
Spotted Wolffish	x	x	x	x	x	x	x																										7	5	0.71	3
Thorny Skate		x	x	x	x	x	x	x	x	x	x	x	x	x	x																		14	4	0.29	3
Winter Skate				x	x	x	x	x	x	x	x	x	x	x																			11	2	0.18	2
Diadramous																																				
Alewife					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x														15	1	0.07	1
American Eel						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						22		0.00	1
American shad					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x													16	1	0.06	1
Atlantic Salmon						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x									19		0.00	1
Atlantic Salmon (Inner Bay of Fundy)						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x										18	0	0.00	1
Atlantic Sturgeon				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	29	2	0.07	1
Atlantic Whitefish					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x										19	1	0.05	1
Striped Bass St. Lawrence Estuary population										x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x						18	0	0.00	1

8.5.2 Cetaceans

The ecological niches that are occupied by cetaceans appear to be defined by water temperature, water depth, and factors that affect the distribution and abundance of their prey (e.g. seabed topography, ocean currents, nutrients, and primary productivity). Although it might be expected that cetaceans, being large well-insulated thermo-regulating mammals, are relatively insensitive to changes in water temperature, this is not the case. Water temperature appears to be the main factor influencing how individuals are distributed (MacLeod 2009). For the purposes of this screening level I&V analysis the approach and analysis of Macleod (2009) has been used to provide an assessment of the sensitivity of cetaceans in Atlantic Basin ocean waters. The analysis of Macleod (2009) separates cetaceans into 4 climatic groupings based on their likely response to changes in water temperature. These include:

- Cosmopolitan species (C) - found in all water temperatures from ice edge to tropical waters. Their distribution may vary with water temperature, sexual segregation, or seasonal migrations.
- Cooler water-limited species (CWL) – found from ice edges of polar waters to waters of a specific temperature range. Distribution is restricted only by warmer water temperatures at lower latitudes. The upper water limit varies.
- Cooler and warmer water-limited species (CWWL) – range within waters of intermediate temperature and do not cross the equator or extend into cooler water close to the poles. These species appear to have both an upper and lower temperature limit to their species ranges.
- Warmer water limited species (WWL) – have a continuous cross-equatorial range in at least one ocean and do not occur in cooler waters of the same ocean. These species are probably only restricted by their ability to occur in cooler waters at the highest latitudes.

A temperature analysis for the Atlantic Basin cetacean species at risk is shown in Table 8-11. From a sensitivity perspective the CWL, CWWL and WWL groupings are all sensitive to water temperature change with the most sensitive being the CWL grouping (Beluga and Northern Bottlenose whales). From a numeric rating perspective CWL grouping could be given a sensitivity rating of 3, CWWL and WWL a rating of 2, and cosmopolitan a rating of 1.

Table 8–11 Temperature ranges for cetacean species at risk in the Atlantic Basin. Range of temperature and sensitivity rating is given (CWL = cold water limited, CWWL =, WWL = warm water limited; and Cosmopolitan).

	Polar				Sub-polar			Temperate															Sub-tropical - Tropical										Rating
		Temperature in degrees Celsius																															
Species		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Beluga Whale		x	x	x	x	x	x																										CWL
Northern Bottlenose Whale		x	x	x	x	x	x	x	x	x	x	x	x	x																			CWL
Sowerby's Beaked Whale					x	x	x	x	x	x	x	x	x	x																			CWWL
North Atlantic Right Whale					x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x										CWWL
Harbour porpoise					x	x	x	x	x	x	x	x	x	x																			CWWL
Blue Whale		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				Cosmopolitan
Fin Whale		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					Cosmopolitan
Humpback Whale		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				Cosmopolitan
Killer Whale		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			Cosmopolitan
Sperm Whale		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			Cosmopolitan
Cuvier's Beaked Whale								x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			WWL

8.5.3 Pinnipeds

The pinniped target species in the Atlantic Basin include four species of seal (Bearded, Ringed, Harp, and Hooded). There have been several key reviews on the impacts and sensitivity of North Atlantic and Arctic mammals, all of which have included these pinnipeds (e.g., Laidre *et al.* 2008; Kovacs 2008; Moore and Huntington 2008). Water temperature is not itself a direct issue for these animals. The key climate change stressor is ice cover, and the dependence of these animals to an ice-covered habitat. Essentially the four seals can be divided into those that are either ice-obligate (Bearded and Ringed – in that they depend on ice as a platform for hunting, breeding and resting) or ice-associated (Hooded and Harp – depend on sea ice mainly for whelping). The ice-obligates are essentially those that are considered Arctic species whilst the ice-associated are considerd sub-Arctic (Laidre et al. 2008).

A sensitivity analysis for these four species to climate change stressors was conducted by Laidre et al (2008). They ranked the species according to eight variables (Table 8–12).

Table 8–12 Ranking of sensitivity of seals to climate change stress factors (from Laidre et al. 2008).

Species	Population	Distribution	Habitat specific	Diet	Migration	Site fidelity	Sea ice changes	Trophic web changes	Rank
Arctic									
Ringed seal	3	3	3	3	3	3	1	3	25
Bearded seal	2	3	2	3	3	3	1	3	23
Sub-Arctic									
Harp seal	3	1	3	3	1	1	1	3	19
Hooded seal	2	1	2	2	1	1	1	2	15

1 = high sensitivity; 2 = intermediate; 3 = low sensitivity

Although this analysis includes a combination of resilience/adaptation aspects, it does indicate that all four species are highly sensitive to sea ice change. The analysis does indicate that the sub-Arctic seals are considered to be more vulnerable to climate change than the Arctic ones and also that all of the seals on the SAR list are highly sensitive to sea ice change.

8.5.4 Reptiles

There are three reptiles in the SAR group (Leatherback, Loggerhead and Kemp's Ridley). Little information is available on the water temperature requirements for the Kemp's Ridley sea turtle. However there is better information for the Loggerhead and Leatherback where these two species exhibit distinctly different preferences to ocean water temperature. The Leatherback, capable of thermoregulating itself, exhibits the same characteristics as the cosmopolitan cetacean group where distribution ranges from ice edge to tropical waters (range 1-27 °C). The Leatherback is therefore not highly sensitive to changes in water temperature. By contrast the Loggerhead exhibits characteristics of warmer water-limited (WWL) as the turtle is not often found in waters below 13 °C (range 14-27 °C). Because of its distribution, it is assumed that the water temperature sensitivity of the Kemp's Ridley sea turtle is most probably similar to that of the Loggerhead. On the basis of water temperature sensitivity for foraging adults the Leatherback could be assigned a numeric value of 1 (low) and the Loggerhead and Kemp's Ridley a numeric value of 2 (intermediate). In each case, an increase in water temperature in Canadian waters will be a positive aspect as it will increase the range of foraging for all of these reptiles.

The potential impacts of climate change on marine turtles has been reviewed by Hawkes et al. (2009) who consider that the main climate change stressors for turtles relate to extreme weather events, coastal processes and environmental conditions at breeding sites in the tropical areas where these turtles nest. The sensitivity of turtle eggs to ambient air temperature is extremely high, as is the availability and condition of the habitat in terms of rainfall, sea level rise, erosion, waves and storm events. In general turtles are not good at expanding the range of their nesting sites (Mike James, DFO Maritimes, pers. comm.), implying that should a combination of climate change factors make nesting sites unsuitable, then the ability to reproduce will be negatively impacted.

8.5.5 Molluscs

There is no information on the sensitivity of the Boreal Awning Clam to climate change conditions. Therefore, for the purposes of this study it has been excluded from further analysis. It is however recommended that COSEWIC include climate change considerations when evaluating the status of this clam as a candidate species at risk species.

8.6 INTEGRATED IMPACTS AND VULNERABILITY ANALYSIS

In conducting an analysis of the impacts of climate change it was considered important to focus on the criteria that COSEWIC uses in assessing and evaluating its species at risk. These criteria relate to whether climate change or a climate change stressor might cause declines in mature individuals, and/or whether there might be a decline in the range occupied by the organism. For the purposes of this analysis it was decided to use a similar approach to that of Chin et al. (2010), but adopting a simpler ranking method. Overall vulnerability was assessed by:

1. Using a simple scale of +, -, or N (neutral) to assess the relative level of interaction for the species.
2. The scale was applied to two areas of impact notably:
    i) Decline in mature individuals
    ii) Decline in range
3. It was also applied to two corresponding attributes of adaptive capacity that organisms would have to possess in order to counter the above-mentioned impacts, notably:
    i) Ability to replace mature individuals
    ii) Ability to move range and hence avoid the stressor
4. Ratings were assigned to each organism based on information available, and then summed to provide an indication as to whether there was an overall positive, neutral or negative ranking, the outcome of which provides an indication of vulnerability. The assessment rating was based on the expected future changes in climate (water temperature) over a 50-year period. This has not been done for the 10-year scenario period as it is apparent that climatic changes over the shorter time scale cannot be separated from current conditions and variability.

It is recognized that this approach has its limitations, particularly as it is based on limited information, has stretched complex aspects into simple assumptions, and It has been carried out by a non-specialist under subjective mode. As with previous sections of this report, it is highly recommended that this analysis be repeated, and refined by a broader corps of specialists.

The ratings for each of the species at risk are presented in Table 8–13. They indicate the following:

- Most of the organisms were given a neutral rating for potential impact on decline in mature individuals. This is not surprising as all of the organisms have evolved to occupy habitats that they have adapted to. A temperature increase in the range of 3 °C is highly unlikely to contribute directly to mortality of many of the species. However, this is not to say that there may be indirect effects that might lead to a decrease in numbers.
- Most of the organisms have the adaptive capacity to move, thereby counteracting the impact of unfavourable habitat change due to temperature increases. By contrast, most of the species at risk have a low adaptive capacity to replace mature individuals and therefore are at high risk should other factors (apart from water temperature) lead to a decline in adult numbers. There is a need for COSEWIC and DFO to ensure that climate change impacts are included in assessments and management plans for the listed species.

- Climatic factors will play a large role in influencing the ranges and distribution of the organisms. The cold water temperature sensitive species are the ones that can be expected to have their distribution reduced whilst the warm water species can be expected to have their distribution expanded. Most of the pelagic species, because of their adaptive capacity for movement, as well as an expected increase in distribution range, will benefit from water temperature increases.
- Certain demersal species (redfish, plaice, wolfish, grenadier, and skate) will be vulnerable to the expected 50-year scenario for water temperature increase (approx. 3 °C). This is primarily because of an anticipated decreased range of distribution as they move northwards into colder waters, as well as their low level adaptive capacity to replace mature individuals.
- Most of the diadramous species will benefit from higher water tempratures across the Atlantic Basin. This is because of their low sensitivity to temperature change, as well as their ability to move and replace mature individuals. However, two of the species (Atlantic Salmon – Inner Bay of Fundy; Atlantic Whitefish) are considered sensitive to climate change because of their restricted range and inability to move from their geographical range.
- Cetacean species have varied vulnerability with some species benefitting (e.g. Cuvier's Beaked Whale, North Atlantic Right Whale) because of increased range and ability to move. Other species are neutral in terms of vulnerability (e.g. Blue Whale, Fin Whale). The species that might be considered vulnerable to climate change warming are Beluga, Harbour porpoise, Northern Bottlenose Whale, and Sowerby's Beaked Whale. The Beluga Whale is probably the most vulnerable because of its restricted habitat distribution (e.g. the population in the Gulf of St Lawrence) and its dependence on ice cover. There is an ambiguity about the Beluga as it is believed to be a relatively flexible species in that it preys upon a large number of different species and can occupy a wide variety of different habitat types, ranging from High Arctic ice-covered waters to sub-Arctic estuaries (Laidre et al. 2008). Because this whale is a relative generalist and is not assumed to be highly vulnerable to climate change, it has been suggested that Belugas may be able to occupy new areas and exploit new ecosystems as sea-ice loss opens new regions within their range.
- All of the pinnipeds can be considered to be vulnerable due to their dependence on ice cover. The sub-Arctic seals (Harp, Hooded) are considered more vulnerable than the Arctic ones (Bearded and Ringed), mainly because of their dependency on sea ice in the subArctic area where sea ice decrease will be higher, and possible inability to shift northwards.
- Turtles can be expected to be positively impacted by warming of waters in the Atlantic Basin as their range for foraging will be increased. The two attributes for the adaptive capacity of turtles give a positive rating as all three species have a relatively high capacity to reproduce and forage

> widely. However this does not necessarily present a true reflection of the situation as there is a high dependency on geographically-fixed, but deteriorating, nesting sites in the Caribbean, which is likely to have an impact on the vulnerability of turtles. In this case it might be more appropriate to evaluate the nesting sites as the assessment target rather than the mature turtles. This does indicate one of the limitations of this assessment approach, but at the same time raises the wider external contributions to climate change risks that DFO has to take into account regarding migrant species at risk.

A summary of this screening approach is presented in Table 8–13. This lists the species that might be expected to benefit positively, neutral ones where the status will remain relatively unchanged, and three categories of vulnerability based on the number of

Table 8–13 Summary table listing vulnerability status of Atlantic Basin marine species at risk to climate change.

Species affected positively	**Neutral Species**	**Species Vulnerable to Climate Change**		
		Low	**Intermediate**	**High**
Atlantic Blue Fin Tuna	Capelin	Acadian Redfish	Atlantic Whitefish	Atlantic Salmon (Inner Bay of Fundy)
Basking Shark	Cusk	American Plaice	Harp Seal	Beluga Whale
Blue Shark	Ocean Pout	Atlantic Wolffish	Hooded Seal	
Porbeagle Shark	Winter Skate	Deepwater Redfish		
Shortfin Mako	American Eel	Northern Wolffish		
White Shark	Blue Whale	Roughhead Grenadier		
Haddock	Fin Whale	Roundnose Grenadier		
Pollock	Humpback Whale	Smooth Skate		
Spiny dogfish	Killer Whale	Spinytail Skate		
Alewife		Spotted Wolffish		
American Shad		Thorny Skate		
Atlantic Salmon		Harbour Porpoise		
Atlantic Sturgeon		Northern Bottlenose Whale		
Striped Bass		Sowerby's Beaked Whale		
Cuvier's beaked Whale		Leatherback Sea Turtle		
Right Whale		Loggerhead Sea Turtle		

Species affected positively	Neutral Species	Species Vulnerable to Climate Change		
		Low	Intermediate	High
Sperm Whale		Kemp's Ridley Sea Turtle Bearded Seal Ringed Seal		

negatives ratings that they received (Table 8–13). The species that are rated with intermediate and high vulnerability are those that are limited by their dependence on geographic habitat location. The group that is in the low vulnerability class represents those that are sensitive to water temperature changes (with exception of the Bearded and Ringed Seals).

Climate change will be positive for foraging turtles in the Atlantic basin, but because their nesting habitats are in areas outside of Canadian waters, and highly vulnerable to climate change factors, these have been placed in this category

As stated at onset, this study has not been able to provide the perfect scientific picture of the situation for all the species. There are many limitations, however, provide some insights into the general impacts and vulnerability of the Atlantic Basin species at risk. It is important that the ACCASP initiate a wider review to consider, and/or refine what is presented through a process involving more expertise and opinion.

This study has also provided opportunity to identify information and research gaps that might improve the predictive capabilities for a vulnerability analysis. There is a need for research and development activity in the following areas:

- Climate change stressor profiles for each of the species that also assess levels and degrees of exposure experienced during life cycle.
- Elucidation of pathway of effects for climate change stressors to distinguish between direct and indirect stressors.
- Sensitivity of species to key climate change stressors
- Temperature ranges to establish upper and lower tolerance limits and the linkage of this with habitat range and availability.
- Climate change adaptive capacity profiles for species
- A methodology that is capable of integrating information so as to provide better confidence in vulnerability assessments

8.7 ACKNOWLEDGEMENTS

This study was supported through the DFO Aquatic Climate Change Adaptation Services Program. Thanks are extended to the following people who contributed valuable opinion, information and advice: Marcia Penney, Andrea Carew, Heidi Schaefer, John Loder, Christine Stortini, Nancy Shackell, Mike James, Charles Hannah.

8.8 REFERENCES

Balcombe, SR., Sheldon, F., Capon, S.J., Bond, NR., Hadwen, WL., Marsh, N. and Bernays, SJ 2011 Climate-change threats to native fish in degraded rivers and floodplains of the Murray]Darling Basin, Australia. Marine and Freshwater Research, 2011, 62, 1099–1114.

Campana SE and Joyce, WE 2004 Temperature and depth associations of porbeagle shark (*Lamna nasus*) in the northwest Atlantic. Fish. Oceanogr. 13:1, 52–64, 2004

Cheung WWL, Lam, VWY, Sarmiento, JL, Kearney, K, Watson, R, and Pauly, D 2009 Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries, 2009, 10, 235-251.

Chin, A, Kyne, PM, Walker, TI, and McAuley, RB (2010) An integrated risk assessment for climate change: analysing the vulnerability of sharks and rays on Australia's Great Barrier Reef Global Change Biology (2010) 16, 1936–1953

Cochrane, K.; De Young, C.; Soto, D.; Bahri, T. (eds). 2009 Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. Rome, FAO. 2009. 212p.

COSEWIC 2012 COSEWIC's Assessment Process and Criteria. http://www.cosewic.gc.ca/pdf/Assessment_process_and_criteria_e.pdf. 18pp.

Froese, R and Pauly, D (eds) 2012 Fish base World Wide Web Electronic Publication. www.fishbase.org, version (06/2012).

Fuessell, HM and Klein, RJT 2006 Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. Climatic Change (2006) 75: 301–329

Hawkes, LA, Broderick, AC, Godfrey, MH, Godley, BJ 2009 Climate Change and Marine Turtles. Endang. Species Res. Vol 7: 137-154.

Hebert, DR Pettipas,G and B. Petrie, 2012: Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2011. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/xxx: vi + 41 p.

Hobday, AJ, T A. Okey, E S Poloczanska, TJ Kunz and AJ Richardson (2007). Impacts of climate change on Australian marine life, CSIRO Marine and Atmospheric Research. Report to the Australian Greenhouse Office, Canberra, Australia. www.greenhouse.gov.au/impacts/publications/ marinelife.html

INTERIS. 2005 Climate Change Risk Assessment for Fisheries and Oceans Canada. Unpublished report prepared for consideration by the Department of Fisheries and Oceans Canada. 56pp.

INTERIS 2012 National Climate Change Risk Profile. 2012 Update. Unpublished report prepared for consideration by the Department of Fisheries and Oceans Canada. 48pp.

IPCC 2007 Climate Change 2007: Synthesis Report. Contribution of Working Groups 1, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html

Jones, RN 2000 Managing Uncertainty in Climate Change Projections – Issues for Impact Assessment. Climate Change, 45, 403-419.

Koehn JD, Hobday AJ, Pratchett MS, Gillanders BM 2011 Climate change and Australian marine and freshwater environments, fishes and fisheries: synthesis and options for adaptation. Marine and Freshwater Research 62, 1148-1164

Kovacs KM and Lydersen, C 2008 Climate change impacts on seal and whales in the north Atlantic Arctic and adjacent shelf seas. Sci Prog. 2008; 91(Pt 2):117-50.

Laidre KL, Stirling I, Lowry LF, Wiig Ø, Heide-Jørgensen M. & Ferguson SH 2008. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. Ecological Applications 18, S97–S125.

Lemmen, DS, Warren, FJ, Lacroix, J, and Bush, E, editors (2008): From Impacts to Adaptation: Canada in a Changing Climate 2007; Government of Canada, Ottawa, ON, 448 p. (http://www.nrcan.gc.ca/earth-sciences/climate-change/community-adaptation/assessments/132)

MacLeod CD 2009 Global Change, Range Changes and Potential Implications for the Conservation of Marine Cetaceans: a Review and Synthesis. Endang. Species Res. Vol 7: 125-136.

Moore, SE and Huntington, HP 2008 Arctic Marine Mammals and Climate Change: Impacts and Resilience. Ecological Applications. 18(2) 157-165.

Pecl GT, Ward T, Doubleday Z, Clarke S, Day J, Dixon C, Frusher S, Gibbs P, Hobday A, Hutchinson N, Jennings S, Jones K, Li X, Spooner D, and Stoklosa R (2011). Risk Assessment of Impacts of Climate Change for Key Marine Species in South Eastern Australia. Part 1: Fisheries and Aquaculture Risk Assessment. Fisheries Research and Development Corporation, Project 2009/070.

Perry R I 2011 Potential Impacts of Climate Change on Marine Wild Capture Fisheries: An Update. Journal of Agricultural Science, 149, 63-75.

Portner ,H.O. and Peck, M.A. 2010 Climate Change Effects on Fishes and Fisheries. Journal of Fish Biology, 77, 1745-1779.

Rose, G.A. 2005 Capelin (*Mallotus villosus*) distribution and climate: a sea “canary” for marine ecosystem change. ICES J. Mar. Sci. (2005) 62 (7): 1524-1530.

Royal Society of Canada 2012. Sustaining Canada's Marine Biodiversity: Responding to the Challenges Posed by Climate Change, Fisheries, and Aquaculture. An Expert panel report. Royal Society of Canada. 316pp. http://rsc-src.ca/documents/RSCMarineBiodiversity2012_ENFINAL.pdf (accessed 21st February 2012)

Schlesinger, M.D., J.D. Corser, K.A. Perkins, and E.L. White. 2011. Vulnerability of at-risk species to climate change in New York. New York Natural Heritage Program, Albany, NY.67pp.

Scott J.S 1982 Depth, Temperature and Salinity Preferences of Common Fishes of the Scotian Shelf. J. Northw. Atl. Fish. Sci., Vol. 3: 29-39.

Scott, W.B., and Scott, M.G. 1988 Atlantic Fishes of Canada. Can.Bull.Fish.Aquat. Sci.219:731pp.

Shackell, N. and Loder, J. 2011 Climate Change and its Effects on Ecosystems Habitats and Biota. In: “State of the Scotian Shelf”. http://coinatlantic.ca/docs/climate-change-and-its-effects-on-ecosystems-habitats-and-biota.pdf. 29pp.

Teck SJ, Halpern BS, Kappel CV, Micheli F, Selkoe KA, Crain CM, Martone R, Shearer C, Arvai J, Fischhoff B, Murray G, Neslo R, Cooke R. Using expert judgment to estimate marine ecosystem vulnerability in the California Current. Ecol Appl. 2010 Jul;20(5):1402-16.

Trends and Projections Working Group 2012. Preliminary Summary of Trends and Projections for the Atlantic Large Aquatic Basin for Use in I&V and S&E Preparations for the Atlantic LAB Risk Assessment. Revised draft released on 23rd April 2012.

20pp. [Editor's note: trends and projections reports now available and listed in Appendix 1 of this report]

West Coast Energy Limited 2005 Vulnerability Assessment of the North East Atlantic Shelf Marine Ecoregion to Climate Change. Report to the World Wildlife Foundation. 79pp. http://awsassets.panda.org/downloads/climatechangeandseas01.pdf

Chapter 9 Community and ecosystem-level effects of climate change in Canadian northwest Atlantic waters

H.P. Benoît* and A.M. MacKinnon

Gulf Fisheries Centre, Fisheries and Oceans Canada, 343 Université Avenue, P. O. Box 5030, Moncton, NB E1C 9B6

*Correspondence: Hugues.Benoit@dfo-mpo.gc.ca

Suggested Citation:

Benoît, H.P., and A.M. MacKinnon. 2013. Community and ecosystem level effects of climate change in Canadian northwest Atlantic waters. Ch. 9 (p. 291–312) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

9.1 INTRODUCTION

Human-induced climate change is expected to effect a number of pressures on aquatic ecosystems in Atlantic Canada and worldwide including, changes in temperature, ocean biogeochemistry (including acidity and dissolved oxygen), ocean currents, river flows, precipitation, salinity, and sea level. Effects of changes in temperature, acidity and dissolved oxygen on aquatic biota at the various levels of biological organization (organismal, population and community/ecosystem) ultimately result from physiological changes at molecular, cellular and whole organism levels (Pörtner and Farrell 2008; Pörtner and Peck 2010). In a first instance, these effects can directly impact organism's physiology and behavior, altering growth, reproductive capacity, mortality and spatiotemporal distribution. The spatiotemporal distribution of organisms whose movement is at least partly determined by passive drift at some or all stages of life is further shaped by changes in river and ocean currents. In turn, organism level changes can affect food web interactions, thereby altering the productivity, structure and dynamics of aquatic ecosystems. Ultimate effects of global warming at the ecosystem level will therefore result from species-specific responses, constituting an indirect effect of climate change that is the focus of this chapter. These responses are likely to be considerably more complex than those predicted based on species-specific considerations (e.g., Harley et al.

2006), and predictions for these emergent system level responses are therefore necessarily much more speculative.

The discussion in this chapter is organized into three sections according to three principal observed and anticipated climate change impacts occurring at the community and ecosystem scale: (1) changes in spatial distribution, (2) changes in the seasonal timing of recurring life history events and (3) changes in ecosystem structure, trophic interactions and productivity. These three categories are inextricably linked. For example, (1) and (2) affect the spatiotemporal overlap of individuals, populations and species, thereby determining the structure and nature of ecological interaction webs. The categories are presented separately only to enhance the clarity of the discussion, and links between them are indicated throughout.

The presentation for each section begins with a general overview of the issue, followed by a brief review of evidence available to date, predictions for changes that may occur as a result of climate change, with a discussion of key uncertainties. Throughout it is assumed that short-term (10 year horizon) effects of climate change relative to the present will largely be indistinguishable from recent variability, and certainly considerably smaller in magnitude than other anthropogenic effects, most notably fishing (e.g., Frank et al. 2005; Benoît and Swain 2008; Shackell et al. 2012). The focus is therefore on effects over an approximately 50-year horizon. Finally, this chapter concludes with a discussion of the key anticipated consequences for DFO programs of ecosystem-level effect of climate change.

9.2 SHIFTS IN GEOGRAPHIC DISTRIBUTION

Theory and recent observations suggest that marine species respond to ocean warming by shifting their latitudinal range (e.g., Perry et al. 2005; Hiddink and Hofstede 2008; Mueter and Litzow 2008) and depth range (Dulvy et al. 2008; Harley 2011), though globally uniform patterns are not expected due to spatial heterogeneity in the rates of temperature change (Burrows et al. 2011). Indeed distributional shifts are expected to be among the first obvious ecological responses to climate change (Frank et al. 1990; Shuter and Post 1990).

9.2.1 Observations—Macrofauna

Studies to date have indicated global average poleward shifts of marine fish distribution between 30 and 130 km/decade (e.g., Perry et al. 2005; Hiddink and Hofstede 2008; Mueter and Litzow 2008). In the NE Atlantic, fish distributions have deepened by 3.5 m/decade in the past few decades (Dulvy et al. 2008). With changes not only in distribution but also abundance, marine fish species' richness has increased in the North and Celtic Seas over the past 30 years (Simpson et al. 2011). This increased biodiversity was associated with a decrease in the size of species in the community, as smaller bodied species with shorter generation times benefited from the envionmental changes. Small bodied species, with rapid population turn-over rates and which generally occupy lower trophic levels, have displayed the most rapid and extensive changes in distribution under past climate changes in the NE and NW Atlantic and the NE Pacific (Perry et al. 2005; Pinsky et al. 2013).

In the NW Atlantic, evidence to date for distributional shifts occurring since the 1960s to 1970s has varied between regions. Beginning in the southern portion of the area, poleward shifts in distribution along with some distributional deepening have been observed for marine fish assemblages in the mid-Atlantic Bight and southern New England (Nye et al. 2009). In contrast, fish with distributions centered on the Gulf of Maine have only shown movement towards deeper water. Marine fishes on the Scotian Shelf and in the southern Gulf of St. Lawrence have shown small longitudinal shifts, but no latitudinal shifts (Pinsky et al. 2013). However, semi-decadal changes in community composition associated with a period of cool bottom waters in these areas during the 1990s is consistent with a response to temperature change (Frank et al. 1996; Carscadden et al. 2001; Benoît and Swain 2008), demonstrating the potential for a longer term effect. This potential for a longer term effect is also demonstrated by an association between temperature anomalies induced by shifts in the North Atlantic Oscillation and changes in the latitudinal diversity gradient of fish (Fisher et al. 2008). Finally, fish communities on the Newfoundland and Labrador shelves generally shifted to deeper waters in the late 1980s, possibly due in part to a temperature effect (Gomes et al. 1995).

9.2.2 Observations—Plankton

Distributions of microscopic planktonic organisms may shift because they are at the mercy of ocean currents or due to local environmental changes. In the NW Atlantic, boreal plankton have shifted farther south (Johns et al. 2001; Reid and Beaugrand 2002; Reid et al. 2007), while in the NE Atlantic, temperate and subtropical plankton species have shifted northward by as much as 1000 km (Beaugrand et al. 2002).

9.2.3 Prediction Under Climate Change

Species' thermal tolerance breadths generally increase with latitude, especially in the Northern Hemisphere (Sunday et al. 2011). Relative to species at lower latitudes, Canadian Atlantic species that are adapted to seasonal temperature variation may be able to withstand greater temperature ranges, allowing for greater plasticity in distributional response. Exceptions might include species whose spawning is limited to the cold waters of Arctic or boreal regions, which are predicted to respond relatively quickly to temperature changes (Rose 2005). Thermal tolerance breadths are narrowest during early life history and after maturation (Pörtner et al. 2006; Pörtner and Farrell 2008) and constraints during these stages are likely to dictate species responses to climate change.

Projecting changes in species distributions based on known environmental preferences, life histories and assumed (modelled) environmental change provides a first approximation of a general pattern of climate change impact on biodiversity (commonly known as the bioclimatic envelope approach). Cheung et al. (2009) predicted global patterns of local extinctions and invasions and their effects on species turnover for the year 2050, relative to 2003, for over one thousand exploited marine fish and invertebrate species under particular climate change scenarios. The authors predicted that distribution centers and poleward range boundaries of most of these species would shift poleward under climate change. Under a high climate change scenario, the median predicted boundary shift was 290 km, though it was considerably higher for pelagic species (600 km) compared to the demersal species that constituted the bulk of the analysis (223 km). The larger predicted shift for pelagic species was explained by a greater dispersal ability combined with a faster projected rate of warming near the surface where pelagic species were usually found. Relative to other areas in the world, the intensity of species shifts into and within Atlantic Canadian waters was predicted to be low to moderate in general, and moderate on the Labrador shelf (Figs. 3 and 4 in Cheung et al. 2009). The intensity of local species disappearance was predicted to be moderate to high in the NE United States and the Scotian Shelf.

The predictions of Cheung et al. (2009) can only be considered as a first approximation of anticipated effects of climate change on biodiversity because they do not incorporate numerous factors known to affect distribution such as species interactions and habitat availability and quality. For example, the rate of range shifts increases by 20-30% by incorporating into the model some simple assumptions concerning ocean acidification and reductions in dissolved oxygen, two changes in biogeochemistry associated with human-induced climate change (Cheung et al. 2011).

Range shifts and possibly expansions are also likely for pathogens and parasites. Populations not previously adversely affected by particular pathogens and parasites, and therefore lacking immunity, could become so as a result of climate change induced co-occurrence and host-switching, increased rates of spread and the disappearance of oceanographic conditions that previously prevented the pathogens from completing their life cycle in a given ecosystem (e.g., Hoberg and Brooks 2008; Macnab and Barber 2011). Adverse effects of pathogens and parasites include decreased stock productivity and harvested product marketability, not to mention the types of community scale changes discussed later.

9.2.4 Key Uncertainties

Distributional changes caused or exacerbated by climate change can potentially take a number of forms, including shifts (displacement), contractions or expansions of distributional area, and the splitting or merging of stocks (Link et al. 2011). The potential consequences for ecosystems and DFO programs depend on the nature of the change.

Distributional changes in general are likely to result in changes in the species composition and possibly the functioning and productivity of the assemblages in which commercially exploited fish stocks occur. This can result from a shift by the commercial stocks themselves, or by species that are components of their food web. This in turn has the potential to affect one or more of the components of productivity of the stocks: recruitment, growth, and natural mortality. A change in productivity can also occur if formerly disjoint stocks with inherently different productivities merge.

Factors other than a direct effect of climate change are likely to influence changes in species distribution over the next half-century and beyond. These include evolutionary changes in response to climate change or other selection pressures, food web interactions, and the availability of suitable habitat for all life stages of each species, each representing an additional potential indirect effect of climate change that may be more important than simple bioclimatic displacements (Van der Putten et al. 2010; Harley 2011; O'Connor et al. 2011). Another principal driver will be the cumulative effect of other anthropogenic activities, for which ecological responses are equally difficult to predict (e.g., Harley et al. 2006; Hsieh et al. 2008).

The predictions made to date are based on an annual distribution and do not incorporate habitat requirements that may vary seasonally. Furthermore, they do not account for local spatial heterogeneity in habitat conditions and the need to maintain life cycle connectivity within populations, for example by minimizing the advection of planktonic life stages away from suitable nursery grounds (e.g., Sinclair 1988).

Models including temperature-dependent competition between species suggest that biological interactions can retard the advance of species into newly suitable habitats, creating lags in climate tracking (Urban et al. 2012). Furthermore, the combined effect of differences in dispersal ability and niche breadth within assemblages could increase the rate of local extirpations above that predicted by climate-driven shifts alone.

9.3. CHANGES IN THE SEASONAL TIMING OF RECURRING LIFE HISTORY EVENTS: PHENOLOGY

Changes in temperature directly affect the timing of life history events (termed phenology) that comprise the life cycle of many aquatic organisms (e.g., Pechenick 1990; Pepin 1991; Benoît et al. 2000; Neuheimer and Taggart 2007). These events include reproduction, hatching, metamorphosis and migration. The timing of these events reflects an adaptation that maximizes organism fitness by increasing the chances that progeny or parents will have access to a place and time that is conducive to growth and survival, i.e., where predation is minimized and opportunities for feeding are maximized.

With climate change, changes in physiology may result in a mismatch between an organism's developmental stage (and associated habitat and food requirements) and the availability of optimal environmental conditions (Visser and Both 2005; Durant et al. 2007). Climate change may also alter the existing coupling between temperature and other environmental cues used to time life history events, such as photoperiod (e.g., Post and Forchhammer 2008). Failure of a population to adapt to these changes will mean a decrease in its productivity (recruitment, survival and/or growth), with possible repercussions to the other species with which it interacts and therefore to food web structure and possible ecosystem-level change (reviewed in Stenseth and Mysterud 2002). The repercussions are potentially very complex given that phenological mismatches can occur throughout an organisms' development and with different interacting species as a result of ontogenetic changes in trophic role (Werner and Gilliam 1984; Polis and Strong 1996; Yang and Rudolph 2010).

9.3.1 Observations of Phenological Changes and Their Community-Level Implications

Globally, studies of phenological change have found that the bloom times of many plants and the arrival of migratory species has occurred earlier in recent time periods (Parmesan and Yohe 2003). The majority of spring and summer events were found to be occurring earlier and more rapidly than previously documented, in a survey of phenological change for over 700 United Kingdom terrestrial, freshwater, and marine taxa (Thackeray et al. 2010). In that study, phenological events of prey species advanced more rapidly than those of predators.

Evidence is mounting that phenological shifts are causing a mismatch between some species and their prey. A review of eleven species showing changes in phenology, ranging from birds to marine plankton, found evidence for a climate change related trophic mismatch in eight species (Visser and Both 2005). Seasonal responses to climate change have differed between species within planktonic communities, resulting in a mismatch between trophic levels and functional groups in freshwater (Winder and Schindler 2004) and marine (Edwards and Richardson 2004) systems. Changes in the seasonal timing of the planktonic prey of larval North Sea cod, along with prey size and abundance, have been linked with the 'gadoid outburst' of the 1970s and the observed poor cod recruitment since the mid-1980s (Beaugrand et al. 2003). In Canadian marine ecosystems, plankton phenology has been linked with recruitment success in northern shrimp *Pandalus borealis* (Koeller et al. 2009; discussed further below), haddock *Melanogrammus aeglefinus* (Platt et al. 2003) and capelin *Mallotus villosus* (DFO 2012). Recruitment success of mackerel *Scomber scombrus* appears to depend on the availability of sufficient and appropriately sized zooplanktonic prey (Castonguay et al. 2008), and is therefore susceptible to seasonal timing of secondary production. In the north Pacific, the timing and magnitude of plankton production has been linked with energy propagation to seabird predators via their fish prey (Mackas et al. 2007; Bertram et al. 2009), demonstrating how simple climate-induced changes in phenology can propagate up trophic levels.

9.3.2 Predictions Under Climate Change and Key Uncertainties

Boreal and temperate aquatic ecosystems, particularly epipelagic systems, are perhaps most vulnerable to the effects of shifting phenology because the seasonal nature of productivity is so pronounced, and the recruitment success of higher trophic levels is highly dependent on a seasonal match with lower trophic level production (e.g., Hjort 1914; Cushing 1974, 1990; Platt et al. 2003; Rubao et al. 2010). If species change the timing of life history events in unison, then the effects on the ecosystem may be minor. However, if species do not change in unison, fitness of many organisms may be dramatically reduced.

Of the above species for which a link has been established between prey phenology and predator recruitment success in Canada, northern shrimp arguably provide the most compelling example of vulnerability to long term changes in plankton phenology. In various shrimp populations, egg development and hatching times are tightly correlated with local bottom water temperatures and bloom timing such that, under average conditions, young shrimp hatch at times when food is available (Koeller et al. 2009). Interannual variability in shrimp recruitment is therefore linked with varying degrees of mismatch between juvenile shrimp occurrence and prey availability (Ouellet et al. 2011). With climate change, there is cause for concern because the hatching of shrimp is dependent on bottom water temperatures, while seasonal productivity of their prey is dependent on temperatures at the surface, which appear to be warming more rapidly. If this trend continues, a mismatch with prey abundance could result, leading to poor shrimp recruitment and ensuing effects to the numerous predators of shrimp (e.g., Worm and Myers 2003; Savenkoff et al. 2007), including commercial fisheries.

However, predictions of the consequences of phenological change beyond first order effects are very uncertain for at least four general reasons. First, even in very simple systems, subtle changes in phenology can dramatically affect the strength and nature of ecological interactions. For example, the annual dominant interaction between two copepod species has been shown to shift between competition and predation depending on climate dependent relative hatching and development times (Maly 1976). In such a case, accounting for changes in both interaction type and strength over the ontogeny of both interacting species would be necessary to predict their short and long term population dynamics. Second, predicting how phenological changes potentially reverberate through a food web is likely to be very speculative given the highly connected nature of marine ecosystems (Link 2002; Dunne et al. 2004; Gaichas and Francis 2008) and the pervasive presence of life history omnivory within food webs (i.e.,, diet change over development) in many species (Hildrew et al. 2007). Third, it is very difficult to predict how species will adapt not only to phenological changes affecting them, but also to changes in the spatial distribution of the species with which they interact. Fourth, trophic mismatches at lower trophic levels may be offset to some degree if primary productivity increases as a result of climate change (Durant et al. 2007; Sherman et al. 2011).

9.4 CHANGES TO FOOD WEBS AND THEIR CONSEQUENCES

Climate driven interannual and seasonal shifts in distribution and local abundance set the template for possible intra and inter-specific interactions. Given co-occurrence, the joint effect of novel ecological interactions and climate change has the potential to dramatically affect the structure, biomass, productivity and dynamics of aquatic communities. A recent review of over 600 studies for terrestrial systems found that climate change can influence virtually every type of species interaction (Tylianakis et al. 2008). Furthermore, because different species or functional groups will not necessarily respond to climate change in a similar way (Van der Putten et al. 2004; Schweiger et al. 2008) and because one or a few 'keystone' species may have particular leverage in a community (e.g., Sanford 1999; Schiel et al. 2004; Zarnetske et al. 2012), short and especially long-term dynamics are difficult to predict. As a result, this section focuses on a discussion of the mechanisms underlying possible food web mediated climate change effects (e.g, Gilman et al. 2010) to highlight the potential scope for change.

9.4.1 Mechanisms Underlying Possible Food Web Mediated Climate Change Effects

Food web mediated climate change effects can be broadly separated into two categories, changes in average state and changes in dynamics. Changes in average state include changes in the interactions web structure (which species interact and how, including both trophic and non-trophic interactions) and changes in the biomass and productivity of different components of the ecosystem. Changes in dynamics include changes in the variability of the biomass and productivity of the various ecosystem components at various time scales, and changes to resilience (i.e., ability of the system to return to its original state following perturbation). While ecosystem state and dynamics are inextricably linked in nature, projected effects of climate change on them are largely discussed separately below for enhanced clarity.

Differences between species in distributional shifts are likely to result in novel assemblages for which there may be no present day analogue, hindering predictions of the possible ecological outcomes. Under climate change, species with strong dispersal abilities and broad ecological niches could out-compete more slowly dispersing species resulting in enhanced extinction risk for organisms with small geographic ranges, specific habitat needs and difficulty dispersing (Urban et al. 2012).

The increased variability in seasonal sea ice quality and seasonal duration in certain NW Atlantic ecosystems is likely to change the distribution and possibly the abundance of key marine mammal top predators, with ensuing effects on their prey (see review in Hammill and Galbraith 2012). Seals that require stable sea ice to successfully breed, such as harp seals (Bajzak et al. 2011) will no longer reproduce in these ecosystems. In contrast, seals that breed most successfully on land, such as grey seals, will be favored by the loss of ice. In the case of harp and grey seals, sea ice loss is likely to result in decreased predation on zooplankton and smaller fish species favored by harp seals (e.g, Savenkoff et al. 2005; Duplisea 2005) and an increased predation pressure on larger fish that appear to be adversely affected by grey seal predation (DFO 2011). An increased impact of grey seals could be direct through predation, parasites, or damage to catch or fishing gear. These impacts may limit recovery of groundfish stocks, as has been reported in the southern Gulf (Benoît et al. 2011; DFO 2011), or result in additional costs to industry as parasites must be removed from landed fish and gear repaired. Additional indirect impacts include changes in fish distribution to avoid predation by seals (Harvey et al. 2010; Harvey and Hammill 2011). Reduction of ice cover may also increase exposure to potential predation from killer whales, whose distribution is limited by the presence of ice.

Warmer water has been shown to favor more numerous but smaller organisms (for example picoplankton), while colder water favors fewer larger organisms (Daufresne et al. 2009; Morán et al 2010; Bode et al. 2011; Reid and Valdes 2011). Furthermore, ocean warming is expected to increase water column stratification, which affects the distribution of nutrients and the assemblage composition of phytoplankton (e.g., Bouman et al. 2011), favoring smaller phytoplankton cells (Li et al. 2009). These patterns suggest that ocean warming could result in a change toward smaller and more numerous phytoplankton (Morán et al. 2010), and smaller-sized species in general (Daufresne et al. 2009). A decrease in phytoplankton size is likely to favor a larger microbial loop as well as predation by smaller zooplankton, resulting in an increase in food chain length that would decrease the efficiency of energy flow from the primary producers to top predators (Li et al. 2006; Beaugrand et al. 2010; Bode et al. 2011; Hilligsøe et al. 2011), resulting in turn in an anticipated decrease in catch potential (Cheung et al. 2011). This may be counterbalanced to some extent if phytoplankton production increases in northern latitudes by mid century as a result of a longer growing season (reviewed in Sherman et al. 2011), or could be exacerbated if production declines as a result of increased stratification (Behrenfeld et al. 2006). It will also be modified by complex effects of ocean acidification amongst primary producers and lower trophic levels that will almost invariably permeate throughout the food web (Blackford 2010). Meanwhile, direct effects of acidification and hypoxia are expected to decrease the productivity of exploited living resources (e.g., Cheung et al. 2011).

The outcome of biological interactions between two or more species can depend on the habitat(s) in which the interactions occur (e.g., Abrahams 1994; Abrahams and Kattenfeld 1997; Poloczanska et al. 2008). For example, this may result from differing habitat adaptations between species or from the availability of physical structures that act as refuges for vulnerable individuals and that generally are known to dampen or extinguish predator-prey cycles (Rosenzweig and Macarthur 1963; Stenseth 1980; Krivan 1998). Climate change can influence the outcome of habitat dependent interactions in two general ways. The first is by affecting a shift in species distributions into novel habitats with different structural properties. The second is by modifying the habitat itself via changes to the nature and amount of biogenic structures (e.g., emergent plants, corals, sponge reefs) or changes to the chemical, physical (e.g., stratification, turbidity) or thermal properties of the abiotic habitat. For example, recent experiments have shown that ice cover affects competition between brown trout, *Salmo trutta*, and Arctic charr, *Salvelinus alpinus*, likely due to temperature- and light-dependent differences in foraging abilities and growth between the two species (Helland et al. 2011). Decreasing ice cover with warmer winters is likely to render trout a superior competitor where these two species co-occur.

Temperature determines the metabolic rate of ectotherms and can alter the energetic requirements of endotherms, in turn affecting feeding, movement and encounter rates of interacting individuals (Brown et al. 2004; Gilman et al. 2010; Kooijman 2010). Biogeochemical changes can similarly affect such rates (e.g., Wu 2002; Dutil et al. 2007; Pörtner and Peck 2010; see reviews in Scarratt et al. 2012 and Scarratt and Starr 2012). Modelling and experiments suggest that warming (and alterations to aquatic biogeochemistry) can either stabilize or destabilize the dynamics of interacting populations depending on how it affects these rates (Vasseur and McCann 2005; Petchey et al. 2010; Rall et al. 2010; Vucic-Pestic et al. 2011). The results are difficult to predict because climate change can differentially affect species in a community due to species-specific physiological optima and ensuing responses to different changes in abiotic conditions (Helmuth et al. 2005). Recent studies on ectothermic terrestrial animals suggest that warming will lead to decreases in energetic efficiencies (ratio of per capita feeding rate to metabolic rate) of predators (Rall et al. 2010; Vucic-Pestic et al. 2011). Based largely on theory, this is generally believed to have a stabilizing effect, resulting in less fluctuation in abundance and a higher probability of returning to the same equilibrium density after a small perturbation, though in extreme cases decreasing ingestion efficiencies may also lead to higher extinction risks because of starvation.

Ocean acidification is likely to affect food web dynamics not only via effects of physiological systems, but also by reducing physical and/or behavioral defenses of prey, thereby increasing predation rates (Doney et al. 2009; Kroeker et al. 2010). For example, in calcifying organisms this may occur via a decrease in the integrity of protective exoskeletons or shells. In fish larvae exposed to acidified waters, maladaptive behaviors have been elicited such as an attraction to the smell of predators and a dangerous willingness to leave shelters, resulting in dramatic reductions in survival and recruitment (Dixson et al. 2010; Munday et al. 2010). Changes in predation rates are known to affect both temporal dynamics and average abundance (Begon and Mortimer 1986).

Large stock reductions due to fishing or other anthropogenic activity have been repeatedly shown to amplify the destabilizing effect of environmental variability as a result of shrinkages of age distributions and geographic extent, and changes in life history (e.g., Anderson et al. 2008; Hseih et al. 2008; Planque et al. 2010; Shackell et al. 2010; Botsford et al. 2011). The effects of harvest and climate change can therefore be synergistic (e.g., Mora et al. 2007). The mechanisms underlying this observation are generally well established and are reviewed in Planque et al. (2010). From an ecosystem perspective, intensive fishing has often been focused on top or upper trophic level species. These species often played an important role in regulating marine communities (e.g., Murdoch et al. 2002; Strong and Frank 2010), and dramatic reductions in their numbers can lead to enhanced sensitivity to short-term climate variability (Perry et al. 2010; Planque et al. 2010). This enhanced variability is likely to have at least two general consequences. First, because population variability is positively associated with extinction risk (reviewed in Vucetich et al. 2000), heightened climate sensitivity may lead to increased chance of extirpation of meta-populations or entire populations. Second, stock productivity is unlikely to be stationary, which will need to be accounted for implicitly or explicitly in management decisions (e.g., King and McFarlane 2006; see discussion in "*Key anticipated consequences for DFO programs*" below). The difficultly will be that past system performance may be a poor indicator of appropriate future reference points.

While host-pathogen relationships are not exclusively trophic, they nonetheless constitute species interactions that are susceptible to the effects of climate change and are therefore briefly discussed here. Because pathogens and many marine organisms are ectothermic, temperature is one of the most important environmental factors affecting the nature, likelihood and severity of infection. This may occur via a number of mechanisms (see examples and reviews in Marcogliese 2001; Harvell et al. 2002; Lafferty 2009; Karvonen et al. 2010). Increases in temperature affect the strength and speed of host immune responses, up to species-specific optima. Beyond these optima, increases in stress associated with climate related changes are likely to result in weakened host immune response. Alterations in life cycle or replication of pathogens could favor the spread and increased outbreaks of certain pathogens but at the same time reduce or inhibit pathogenesis of others thereby releasing their hosts from current diseases (e.g., Harvell et al. 2002). Extended periods of warmer temperatures may also allow certain endemic pathogens to achieve higher abundance for longer periods, increasing the frequency and severity of infections (Marcos-López et al. 2010). Even in cases of sub-lethal infection, resulting additional physiological stress in the host could, in turn, reduce their fitness by altering behaviors and performance that affect things like susceptibility to predation and reproduction.

9.5 KEY ANTICIPATED CONSEQUENCES FOR DFO PROGRAMS

9.5.1 Harvest Levels and the Application of the Precautionary Approach

Shifts in spatial distribution and phenology, and changes to food webs will certainly cause changes in the productivity of exploited living aquatic resources, as discussed above. As productivity changes, so too should associated management reference points, creating at least three key challenges for DFO Science and Ecosystem and Fisheries Management Sectors. The first will be in ensuring that Science has in place sufficient monitoring along with well tested analytical tools and approaches to reliably detect changes in productivity with only short delays. The second will be in developing the science to determine when and how reference points should be changed when faced with evidence of productivity change, and some of this work is already underway (e.g., http://www.dfo-mpo.gc.ca/csas-sccs/Schedule-Horraire/2011/12_13-15-eng.html). The third will be in developing management strategies that are robust to unknown sudden or progressive productivity change that may temporarily go unnoticed. Failure to meet these challenges could lead to a mismatch between exploitation rates and the ability of stocks to support them, resulting in unsustainable exploitation in some stocks and missed opportunities for economic prosperity and providing sustenance to people from other stocks. Priority for assessment and an enhanced level of precaution should be given to populations occurring at the edge of their species 'range, as these may be the most vulnerable and quickest to respond to effects of climate change (Brander 2010).

Medium to long-term decision making for fisheries will require the capacity to anticipate the consequences of management under different scenarios of climate change. Models that include probable trophic interactions that integrate the effects of fishing and environmental change across trophic levels and that properly reflect knowledge uncertainty will be required, as has been recently done for cod in the Baltic Sea (Lindegren et al. 2010).

9.5.2 Keeping up With Changes in Stock Boundaries

Existing management area boundaries for many harvested finfish and other stocks were largely established to circumscribe the main biological areas of the stocks. Likewise, fisheries independent surveys have generally been designed to largely sample entire stock areas, so as not to confound changes in abundance and distribution. With climate change, the distribution of many stocks is expected to shift beyond the boundaries of these historical stock and survey areas. Though fisheries-independent surveys cover much of the NW Atlantic, these are generally not synoptic (i.e., undertaken in different seasons in the different areas) and do not necessarily use the same gear (Chadwick et al. 2007), which complicates comparisons between surveys and therefore the tracking of distributional shifts. There is therefore strong potential for a discrepancy between actual and apparent stock sizes, potentially leading to the application of inappropriate management actions. Enhanced standardization of survey designs or the estimation of robust conversion factors to standardize survey data post hoc could help minimize this problem.

Distributional shifts across management boundaries will also require enhanced vigilance concerning stock identification, as stock areas move and their boundaries potentially become blurred (Link et al. 2011). Because biological productivity and responses to harvesting occur at the scale of stocks (populations), management applied at this scale is most likely to be effective. As with the changes in productivity described above, failure to properly delimit the biological units of stocks risks creating a mismatch between exploitation rates and stock productivity. Regular review of stock identification could help minimize such mismatches.

Shifts in stock distributions are likely to increase conflicts among resource users. As a stock moves into an area, local resource users are likely to claim new or increased access, while users in the former stock area are likely to want to maintain what they perceive as their historical share. Increased demands on fisheries managers for revisions to actual or perceived resource allocations are to be expected.

9.5.3 Increased Attention to the Need to Protect/Enhance Older and Larger Spawners in Exploited Living Resources

In many fish species, older and larger spawners are known not only to be more fertile, but also to produce larger and more viable eggs and larvae, and to spawn in different and more dispersed temporal and spatial windows (e.g., Trippel et al. 1997; Marteinsdottir and Thorarinsson 1998; Berkeley et al. 2004a, b). This bet-hedging strategy means that the population reproductive potential is greater if larger/older individuals are proportionally more abundant, as 1) more young are produced, 2) individual post-hatch larvae are able to sustain longer periods of starvation because of greater energy reserves and 3) larvae are present over a potentially greater area and for a more protracted time, increasing the chances of an overlap with planktonic food resources. Protecting older and larger fish by reducing fishing mortality and through the use of selective fishing is likely to be the most effective manner of buffering against the effects of recruitment variability and failure driven by climate induced changes in phenology (e.g, Francis et al. 2007; Planque et al. 2010).

9.5.4 Pressures Created by Changes in the Diversity, Intensity and Frequency of Agents that are Infectious to Fish

Changes in the nature, intensity and frequency of interactions between pathogens or parasites and their hosts are likely to create demands for new science and additional monitoring. For example, there is likely to be a need to conduct research on new infectious agents that may arrive in Canadian waters in order to better understand their significance and impact in aquatic animal populations, and to develop new diagnostic tests in cases where the impacts are serious. Increased regulatory disease testing may be required under the National Aquatic Animal Health Program, if the epidemiology of endemic pathogens changes or as a result of the arrival of non-endemic pathogens, in order to protect Canada's aquatic resources from the threat and spread of disease and to maintain market access of Canadian seafood products.

9.6 REFERENCES

Abrahams, M.V. 1994. Risk of predation and its influence on the relative competitive abilities of two species of freshwater fishes. Can. J. Fish. Aquat. Sci. 51: 1629–1633.

Abrahams, M.V., and Kattenfeld, M.G. 1997. The role of turbidity as a constraint on predator–prey interactions in aquatic environments. Behav. Ecol. Sociobiol. 40: 169–174.

Anderson, C.N.K., Hseih, C.-h., Sandin, S.A., Hewitt, R., Hollowed, A.B., Beddington, J.R., May, R.M., and Sugihara, G. 2008. Why fishing magnifies fluctuations in fish abundance. Nature 452: 835-839.

Bajzak, C., Hammill, M.O., Stenson, G.B., and Prinsenberg, S. 2011. Drifting away: implications of changes in ice conditions for a packice-breeding phocid, the harp seal (*Pagophilus groenlandicus)*. Can. J. Zool. 89: 1050–1062.

Beaugrand, G., Brander, K.M., Lindley, J.A., Souissi, S., and Reid, P.C. 2003. Plankton effect on cod recruitment in the North Sea. Nature 426: 661-664.

Beaugrand. G., Edwards, M., and Legendre, L. 2010. Marine biodiversity, ecosystem functioning and carbon cycles. Proc. Nat. Acad. Sci. USA 107:10120-10124.

Beaugrand, G., Reid, P.C., Ibañez, F., Lindley, J.A., and Edwards, M. 2002. Reorganization of North Atlantic Marine Copepod Biodiversity and Climate. Science 296: 1692-1694.

Begon, M., and Mortimer, M. 1986. Population ecology: A unified study of animals and plants, 2nd ed. Blackwell Scientific Publications, London UK. 220 pp.

Behrenfeld, M.J., O'Malley, R.T., Siegel, D.A., McClain, C.R., Sarmiento, J.L., Feldman, G.C., Milligan, A.J., Falkowski, P.G., Letelier, R.M., and Boss, E.S. 2006. Climate-driven trends in contemporary ocean productivity. Nature 444: 752-755.

Benoît, H.P., and Swain, D.P. 2008. Impacts of environmental change and direct and indirect harvesting effects on the dynamics of a marine fish community. Can. J. Fish. Aquat. Sci. 65: 2088-2104.

Benoît, H.P., Pepin, P., and Brown, J.A.. 2000. Patterns of metamorphic age and length in marine fishes, from individuals to taxa. Can. J. Fish. Aquat. Sci. 57:856-869.

Benoît, H.P., Swain, D.P., Bowen, W.D., Breed, G. A., Hammill, M.O., and Harvey, V. 2011. Evaluating the potential for grey seal predation to explain elevated natural mortality in three fish species in the southern Gulf of St. Lawrence? Mar. Ecol. Prog. Ser. 442:149-167.

Berkeley, S.A., Chapman, C., and Sogard, S.M. 2004a. Maternal age as a determinant of larval growth and survival in a marine fi sh, *Sebastes melanops*. Ecology 85:1258-1264.

Berkeley, S.A., Hixon, M.A., Larson, R.J., and Love, M.S. 2004b.Fisheries sustainability via protection of age structure and spatial distribution of fish populations. Fisheries 29: 23-32.

Bertram, D.F., Harfenist, A., and A. Hedd. 2009. Seabird nestling diets reflect latitudinal temperature-dependent variation in availability of key zooplankton prey populations. Mar. Ecol. Prog. Ser.393: 199–210.

Blackford, J.C. 2010. Predicting the impacts of ocean acidification: challenges from an ecosystem perspective. J. Mar. Syst. 81: 12–18.

Bode, A., Hare, J., Li, W.K.W., Moran, X.A.G., and Valdes, L. 2011. Chlorophyll and primary production in the North Atlantic. pp. 77–102 *in* ICES status report on climate change in the North Atlantic, P.C. Reid and L. Valdes (eds). ICES Cooperative Research Report 310.

Botsford, L.W., Holland, M.D., Samhouri, J.F., White, J.W., and Hastings, A. 2011. Importance of age structure in models of the response of upper trophic levels to fishing and climate change. ICES J. Mar. Sci., 68: 1270–1283.

Bouman, H.A, Ulloa, O., Barlow, R., Li, W.K.W., Platt, T., Zwirglmaier, K., Scanlan, D.J., Sathyendranath, S. 2011. Water-column stratification governs the community structure of subtropical marine picophytoplankton. Environ. Microbiol. Rep., 3: 473-482.

Brander, K. 2010. Impacts of climate change on fisheries. J. Mar. Syst. 79: 389-402.

Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M., and West, G.B. 2004. Toward a metabolic theory of ecology. Ecology 85: 1771-1789.

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., and Richardson, A.J. 2011. The pace of shifting climate in marine and terrestrial ecosystems. Science 334: 652-655.

Carscadden, J.E., Frank, K.T., and Leggett, W.C. 2001. Ecosystem changes and the effects on capelin (*Mallotus villosus*), a major forage species. Can. J. Fish. Aquat. Sci 58: 73-85.

Castonguay, M., Plourde, S., Robert, D., Runge, J.A., and Fortier, L. 2008. Copepod production drives recruitment in a marine fish. Can. J. Fish. Aquat. Sci. 65: 1528-1531.

Chadwick, E.M.P., Brodie, W., Clark, D., Gascon, D., and Hurlbut, T. R. 2007. History of annual multi-species trawl surveys on the Atlantic coast of Canada. Atlantic Zonal Monitoring Program Bulletin, 6: 25-42. (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/docs/bulletin_6_05.pdf).

Cheung, W.W.L., Dunne, J., Sarmiento, J.L., and Pauly, D. 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES J. Mar. Sci., 68: 1008-1018.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., and Pauly, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish Fish. 10: 235-251.

Cushing, D.H. 1974. Sea fisheries research. John Wiley and Sons, New York, New York, USA.

Cushing, D.H. 1990. Plankton production and year-class strength in fish population: an update of the match/mismatch hypothesis. Adv. Mar. Biol., 26: 250−293

Daufresne, M., Lengfellner, K., and Sommer, U. 2009. Global warming benefits the small in aquatic ecosystems. Proc. Nat. Acad. Sci. USA 106: 12788-12793.

DFO, Department of Fisheries and Oceans. 2011. Impacts of grey seals on fish populations in Eastern Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/071: 48 pp.

DFO, Department of Fisheries and Oceans. 2012. Results and recommendations from the Ecosystem Research Initiative – Newfoundland and Labrador's Expanded Research on Ecosystem Relevant but Under-Surveyed Splicers. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/058.

Dixson, D.L., Munday, P.L., and Jones, G.P. 2010. Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. Ecol. Lett. 13.: 68-75.

Doney, S.C., Fabry, V.J., Feely, R.A., and Kleypas, J.A. 2009. Ocean acidification: the other CO_2 problem. Annu. Rev. Mar. Sci. 1: 169–192.

Dutil, J.-D., Sylvestre, E.L., Gamache, L., Larocque, R., and Guderley, H. 2007. Burst and coast use, swimming performance and metabolism of Atlantic cod *Gadus morhua* in sub-lethal hypoxic conditions. J. Fish. Biol. 71: 363–375.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R., and Skjoldal, H.R. 2008. Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. J. Appl. Ecol. 45: 1029-1039.

Dunne, J.A., Williams, R.J., and Martinez, N.D. 2004. Network structure and robustness of marine food webs. Mar. Ecol. Prog. Ser. 273: 291-302.

Duplisea, D.E. 2005. Running the gauntlet: the predation environment of small fish in the northern Gulf of St Lawrence, Canada. ICES J. Mar. Sci. 62: 412-416.

Durant, J.M., Hjermann, D.O., Ottersen, G., and N.C. Stenseth. 2007. Climate and the match or mismatch between predator requirements and resource availability. Clim. Res., 33: 271

Edwards, M., and Richardson, A.J. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430: 881-884.

Fisher, J.A.D., Frank, K.T., Leggett, W.C., Shackell, N.L., and Petrie, B. 2008. Temporal dynamics within a contemporary latitudinal diversity gradient. Ecol. Lett. 11: 883-897.

Francis, R.C., Hixon, M.A., Clarke, M.E., Murawski, S.A., and Ralston, S. 2007. Ten commandments for ecosystem-based fisheries scientists. Fisheries 32: 217-233.

Frank, K.T., Perry, R.I., and Drinkwater, K.F. 1990. Predicted response of Northwest Atlantic invertebrate and fish stocks to CO_2 induced climate change. Trans. Am. Fish. Soc. 119:353–365.

Frank, K.T., Carscadden, J.E., and Simon, J.E. 1996. Recent excursions of capelin (*Mallotus villosus*) to the Scotian Shelf and Flemish Cap during anomalous hydrographic conditions. Can. J. Fish. Aquat. Sci., 53: 1473-1486.

Frank, K.T., Petrie, B., Choi, J.S., and Leggett, W.C. 2005. Trophic cascades in a formerly cod-dominated ecosystem. Science 308: 1621-1623.

Gaichas, S.K., and Francis, R.C. 2008. Network models for ecosystem-based fishery analysis: a review of concepts and application to the Gulf of Alaska marine food web. Can. J. Fish. Aquat. Sci. 65: 1965-1982.

Gilman, S.E., Urban, M.C., Tewksbury, J., Gilchrist, G.W., and Holt, R.D. 2010. A framework for community interactions under climate change. Trends Ecol. Evol. 25: 325-331.

Gomes, M.C., Haedrich, R.L., and Villagarcia, M.G. 1995. Spatial and temporal changes in the groundfish assemblages on the North-East Newfoundland/Labrador Shelf, north-west Atlantic, 1978-1991. Fish. Oceanogr. 4: 85-101.

Hammill, M.O., and Galbraith, P.S. 2012. Changes in seasonal ice-cover and its effect on marine mammals. Pp 24-30 *in* State-of-the-Ocean report for the Gulf of St. Lawrence Integrated Management (GOSLIM) area, H.P. Benoît, J.A. Gagné, C. Savenkoff, P. Ouellet, and M.-N. Bourassa (eds). Can. Manuscr. Rep. Fish. Aquat. Sci. 2986: viii+73.

Harley, C.D.G., Hughes, A.R., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Rodriguez, L.F., Tomanek, L., and Williams, S.L. 2006. The impacts of climate change in coastal marine systems. Ecol. Lett., 9: 228-241.

Harley, C. D. G. 2011. Climate change, keystone predation, and biodiversity loss. Science, 334: 1124-1127.

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S., Samule, M.D. 2002. Climate warming and disease Risks for terrestrial and marine biota. Science 296: 2158–2162.

Harvey, V., and Hammill, M. O. 2011. Variations on spatial distribution on fish abundance in eastern Scotian shelf over the past four decades. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/132. iv + 12 p.

Harvey, V., Hammill, M., and Swain, D.P. 2010. Summer overlap between a central-place forager and its prey in the southern Gulf of St. Lawrence. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/131: vi + 46 pp.

Helland, I.P., Finstad, A.G., Forseth, T., Hesthagen, T., and Ugedal, O. 2011. Ice-cover effects on competitive interactions between two fish species. J. Anim. Ecol., 80: 539–547.

Helmuth, B., Kingsolver, J.G., and Carrington, E. 2005. Biophysics, physiological ecology, and climate change: Does mechanism matter? Annu. Rev. Physiol., 67: 177–201.

Hiddink, J.G., and Hofstede, R.T. 2008. Climate induced increases in species richness of marine fishes. Glob. Change Biol. 14: 453–460.

Hildrew, A., Raffaelli, D., and Edmonds-Brown, R. (eds.). 2007. Body size: The structure and function of aquatic ecosystems. Cambridge University Press, Cambridge UK. 343 p.

Hilligsøe, K.M., Richardson, K., Bendtsen, J., Sørensen, L.-L., Nielsen, T.G., and Lyngsgaard, M.M. 2011. Linking phytoplankton community size composition with temperature, plankton food web structure and sea–air CO_2 flux. Deep Sea Res. Part 1, 58:826-838.

Hjort, J. 1914 Fluctuations in the great fisheries of northern Europe. Rapp. Conserv. Explor. Mer 20: 1−228

Hoberg, E.P., and Brooks, D.R.. 2008. A macroevolutionary mosaic: episodic host-switching, geographical colonization and diversification in complex host–parasite systems. J. Biogeog., 35: 1533-1550.

Hseih, C.-h., Reiss, C.S., Hewitt, R.P., and Sugihara, G. 2008. Spatial analysis shows that fishing enhances the climatic sensitivity of marine fishes. Can. J. Fish. Aquat. Sci. 65: 947-961.

Johns, D.G., Edwards, M., and Batten, S.D. 2001. Arctic boreal plankton species in the Northwest Atlantic. Can. J. Fish. Aquat. Sci. 58: 2121-2124.

Karvonen, A., Rintamäki, P., Jokela, J., and Valtonen, E.T. 2010. Increasing water temperature and disease Risks in aquatic systems: Climate change increases the Risk of some, but not all, diseases. Int. J. Parasitol. 40: 1483-1488.

King, J.R., and McFarlane, G.A., 2006. A framework for incorporating climate regime shifts into the management of marine resources. Fish. Manag. Ecol., 13: 93–102.

Koeller, P., Fuentes-Yaco, C., Platt, T., Sathyendranath, S., Richards, A., Ouellet, P., Orr, D., Skuladottir, U., Wieland, K., Savard, L., and Aschan, M. 2009. Basin-scale coherence in phenology of shrimps and phytoplankton in the North Atlantic Ocean. Science 324: 791-793.

Kooijman, S.A.L.M. 2010. Dynamic energy budget theory for metabolic organization, 3rd ed. Cambridge University Press, Cambridge UK. 514 pp.

Krivan, V. 1998. Effects of optimal antipredator behavior of prey on predator-prey dynamics: The role of refuges. Theor. Pop. Biol., 53:131-142.

Kroeker, K.J., Kordas, R.L., Crim, R.N., and Singh, G.G. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol. Lett. 13: 1419-1434.

Lafferty, K.D., 2009. The ecology of climate change and infectious diseases. Ecology 90: 888–900.

Li, W.K.W., Harrison, W.G., and Head, E.J.H. 2006. Coherent assembly of phytoplankton communities in diverse temperate ocean ecosystems. Proc. Roy. Soc. B 273: 1953–1960

Li, W.K.W., McLaughlin, F.A., Lovejoy, C., and Carmack, E.C. 2009. Smallest algae thrive as the Arctic Ocean freshens. Science 326: 539.

Lindegren, M., Mollmann, C., Nielsen, A., Brander, K.M., MacKenzie, B.A., and Stenseth, N.C. 2010. Ecological forecasting under climate change: the case of Baltic cod. Proc. R. Soc. B. 277: 2121-2130.

Link, J.S. 2002. Does food web theory work for marine ecosystems? Mar. Ecol. Prog. Ser. 230: 1-9.

Link, J.S., Nye, J.A., and Hare, J.A. 2011. Guidelines for incorporating fish distribution shifts into a fisheries management context. Fish Fish. 12: 461-469

Mackas, D.L., Batten, S., and M. Trudel. 2007. Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. Prog. Oceanog.75: 223–252.

Macnab, V., and Barber, I. 2011. Some (worms) like it hot: fish parasites grow faster in warmer water, and alter host thermal preferences. Glob. Change Biol.; DOI: 10.1111/j.1365-2486.2011.02595.x

Maly, E.J. 1976. Resource overlap between co-occurring copepods – effects of predation and environmental fluctuation. Can. J. Zool., 54: 933–940

Marcogliese, D.J., 2001. Implications of climate change for parasitism of animals in the aquatic environment. Can. J. Zool. 79: 1331–1352.

Marcos-López, M., Gale, P., Oidtmann, B.C., and Peeler, E.J. 2010. Assessing the impact of climate change on disease emergence in freshwater fish in the United Kingdom. Transbound. Emerg. Dis. 57: 293-304

Marteinsdottir, G., and Thorarinsson, K. 1998. Improving the stock-recruitment relationship in Icelandic cod (*Gadus morhua*) by including age diversity of spawners. Can. J. Fish. Aquat. Sci. 55:1372-1377

Mora, C., Metzger, R., Rollo, A., and Myers, R.A. 2007. Experimental simulations about the effects of overexploitation and habitat fragmentation on populations facing environmental warming. Proc. R. Soc. B. 274: 1023-1028.

Morán, X.A.G., Lopez-Urrutia, A., Calvo-Diax, A., and Li, W.K.W.. 2010. Increasing importance of small phytoplankton in a warmer ocean. Glob. Change Biol. 16: 1137–1144.

Mueter, F.J., and Litzow, M.A. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. Ecol. Applic., 18: 309–320.

Munday, P.L., Dixson, D.L., McCormick, M.I., Meekan, M., Ferrari, M.C.O., and Chivers, D.P. 2010. Replenishment of fish populations is threatened by ocean acidification. Proc. Nat. Acad. Sci USA107: 12930–12934.

Murdoch, W.W., Kendall, B.E., Nisbet, R.M., Briggs, C.J., McCauley, E., and Bolser, R. 2002. Single-species models for many-species food webs. Nature 417: 541-543.

Neuheimer, A.B., and Taggart, C.T. 2007. The growing degree-day and fish size-at-age: the overlooked metric. Can. J. Fish. Aquat. Sci., 64: 375-385.

Nye, J.A., Link, J.S., Hare, J.A., and Overholtz, W.J. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Mar. Ecol. Prog. Ser. 393: 111-129.

O'Connor, M.I., Selig, E.R., Pinsky, M.L., and Altermatt, F. 2011. Toward a conceptual synthesis for climate change responses. Glob. Ecol. Biogeogr. DOI: 10.1111/j.1466-8238.2011.00713.x: no.

Ouellet, P., Fuentes-Yaco, C.s., Savard, L., Platt, T., Sathyendranath, S., Koeller, P., Orr, D., and Siegstad, H. 2011. Ocean surface characteristics influence recruitment variability of populations of northern shrimp (*Pandalus borealis*) in the Northwest Atlantic.. ICES J. Mar. Sci. 68: 737-744.

Parmesan, C., and Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Pechenick, J.A. 1990. Delayed metamorphosis by larvae of benthic marine invertebrates: does it occur? Is there a price to pay? Ophelia, 32: 63–94.

Pepin, P. 1991. Effect of temperature and size on development, mortality, and survival rates of the pelagic early life history stages of marine fish. Can. J. Fish Aquat. Sci. 48: 503-518.

Perry, A.L., Low, P.J., Ellis, J.R., and Reynolds, J.D. 2005. Climate change and distribution shifts in marine fishes. Science 308: 1912-1915.

Perry, R.I., Cury, P., Brander, K., Jennings, S., Mollmann, C., and Planque, B. 2010. Sensitivity of marine systems to climate and fishing: Concepts, issues and management responses. J. Mar. Syst. 79: 427-435.

Petchey, O.L., Brose, U., and Rall, B.C. 2010. Predicting the effects of temperature on food web connectance. Phil.l Trans. Roy. Soc. B, 365: 2081-2091.

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L., and Levin, S. A. 2013. Marine taxa track local climate velocities. *Science* 341: 1239-1242, doi: 10.1126/science.1239352.

Planque, B., Fromentin, J.M., Cury, P., Drinkwater, K.F., Jennings, S., Perry, R.I., and Kifani, S. 2010. How does fishing alter marine populations and ecosystems sensitivity to climate? J. Mar. Syst. 79: 403-417.

Platt, T., Fuentes-Yaco, C., and Frank, K.T. 2003. Spring algal bloom and larval fish survival. Nature 423: 398–399.

Polis, G.A., and Strong, D.R. 1996. Food web complexity and community dynamics. Am. Nat. 147: 813-846.

Poloczanska, E.S., Hawkins, S.J., Southward, A.J., and Burrows, M.T. 2008. Modeling the response of populations of competing species to climate change. Ecology 89: 3138-3149.

Pörtner, H.O., and Farrell, A.P. 2008. Physiology and climate change. Science 322: 690-692.

Pörtner, H.O., and Peck, M.A. 2010. Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J. Fish Biol. 77: 1745-1779.

Post, E., and Forchhammer, M. C. 2008. Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch. Phil. Trans. R. Soc. B, 363: 2369–2375.

Rall, B.C., Vucic-Pestic, O., Ehnes, R.B., Emmerson, M., and Brose, U. 2010. Temperature, predator-prey interaction strength and population stability. Glob. Change Biol. 16: 2145-2157.

Reid, P.C., and Beaugrand, G. 2002. Interregional biological responses in the North Atlantic to hydrometeorological forcing. Pp 27-48 *in* Large Marine Ecosystems of the North Atlantic: Changing states and sustainability. Sherman, K., and Skjoldal, H.-R. (eds). Elsevier Science BV, Amsterdam, The Netherlands.

Reid, P.C., and Valdes, L. 2011. ICES status report on climate change in the North Atlantic. ICES Cooperative Research Report 310. 262 pp.

Reid, P.C., Johns, D.G., Edwards, M., Starr, M., Poulin, M., and Snoeijs, P. 2007. A biological consequence of reducing Arctic ice cover: arrival of the Pacific diatom *Neodenticula seminae* in the North Atlantic for the first time in 800,000 years. Glob. Change Biol. 13: 1910-1921.

Rose, G.A. 2005. On distributional responses of North Atlantic fish to climate change. ICES J. Mar. Sci. 62: 1360-1374.

Rosenzweig, M.L., and Macarthur, R.H. 1963. Graphical representation and stability conditions of predator-prey interactions. Am. Nat., 97:209-223

Rubao, J.I., Edwards, M., Mackas, D.L., Runge, J.A., and Thomas, A.C.. 2010. Marine plankton phenology and lifehistory in a changing climate: currentresearch and future directions. J. Plank. Res., 32: 1355–1368.

Sanford, E. 1999. Regulation of keystone predation by small changes in ocean temperature. Science, 283: 2095–2097.

Savenkoff, C., M. Castonguay, R. Méthot, D. Chabot, and M. O. Hammill. 2005. Input data and parameter estimates for ecosystem models of the northern Gulf of St. Lawrence (2000–2002). Can. Tech. Rep. Fish. Aquat. Sci. 2588: v+91 pp.

Savenkoff, C., Castonguay, M., Chabot, D., Hammill, M.O., Bourdages, H., and Morissette, L. 2007. Changes in the northern Gulf of St. Lawrence ecosystem estimated by inverse modelling: Evidence of a fishery-induced regime shift? Est. Coast. Shelf Sci. 73: 711–724

Scarratt, M., and Starr, M. 2012. Ocean acidification impacts in the Gulf of St. Lawrence. Pp 15-24 *in* State-of-the-Ocean report for the Gulf of St. Lawrence Integrated Management (GOSLIM) area, H.P. Benoît, J.A. Gagné, C. Savenkoff, P. Ouellet, and M.-N. Bourassa (eds). Can. Manuscr. Rep. Fish. Aquat. Sci. 2986: viii+73.

Scarratt, M., Chabot, D., and Gilbert, D. 2012. Hypoxia in the Estuary and Gulf of St. Lawrence. Pp 10-15 *in* State-of-the-Ocean report for the Gulf of St. Lawrence Integrated Management (GOSLIM) area, H.P. Benoît, J.A. Gagné, C. Savenkoff, P. Ouellet, and M.-N. Bourassa (eds). Can. Manuscr. Rep. Fish. Aquat. Sci. 2986: viii+73.

Schiel, D.R., Steinbeck, J.R., and Foster, M.S. 2004. Ten years of induced ocean warming causes comprehensive changes in marine benthic communities. Ecology, 85: 1833–1839.

Schweiger, O., Settele, J., Kudrna, O., Klotz, S., and Kühn, I. 2008. Climate change can cause spatial mismatch of trophically interacting species. Ecology, 89: 3472–3479.

Shackell, N.L., Bundy, A., Nye, J.A., and Link, J.S. 2012. Common large-scale responses to climate and fishing across Northwest Atlantic ecosystems. ICES J. Mar. Sci., 69: 151-162.

Shackell, N.L., Frank, K.T., Fisher, J.A.D., Petrie, B., and Leggett, W.C. 2010. Decline in top predator body size and changing climate alter trophic structure in an oceanic ecosystem. Proc. R. Soc. B. 277: 1353-1360.

Sherman, K., O'Reilly, J., Belkin, I.M., Melrose, C., and Friedland, K.D. 2011. The application of satellite remote sensing for assessing productivity in relation to fisheries yields of the world's large marine ecosystems. ICES J. Mar. Sci. 68: 667-676.

Shuter, B.J., and Post, J.R. 1990. Climate, population viability, and the zoogeography of temperate fishes. Trans. Am. Fish. Soc. 119:314–336

Simpson, S.D., Jennings, S., Johnson, M.P., Blanchard, J.L., Schön, P.-J., Sims, D.W., and Genner, M.J. 2011. Continental shelf-wide response of a fish assemblage to rapid warming of the sea. Curr. Biol. 21: 1565-1570.

Sinclair, M. 1988. Marine Populations: An Essay on Population Regulation and Speciation.Seattle, WA: University of Washington Press.

Stenseth, N.C. 1980. Spatial heterogeneity and population stability: some evolutionary consequences. Oikos, 35:165-184.

Stenseth, N.C., and Mysterud, A. 2002. Climate, changing phenology, and other life history traits: Nonlinearity and match-mismatch to the environment. Proc. Nat. Acad. Sci. USA 99: 13379-13381.

Strong, D.R., and Frank, K.T., 2010. Human involvement in food webs. Ann. Rev. Envir. Res., 35:1-23.

Sunday, J.M., Bates, A.E., and Dulvy, N.K. 2011. Global analysis of thermal tolerance and latitude in ectotherms. Proc. R. Soc. B. 278: 1823-1830.

Thackeray, S.J., Sparks, T.H., Frederiksen, M., Burthe, S., Bacon, P.J., Bell, J.R., Botham, M.S., Brereton, T.M., Bright, P.W., Carvalho, L., Clutton-Brock, T., Dawson, A., Edwards, M., Elliott, J.M., Harrington, R., Johns, D., Jones, I.D., Jones, J.T., Leech, D.I., Roy, D.B., Scott, W.A., Smith, M., Smithers, R.J., Winfield, I.J., and Wanless, S. 2010. Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments. Glob. Change Biol. 16: 3304-3313.

Trippel, E.A., Kjesbu, O.S., and Solemdal, P. 1997. Effects of adult age and size structure on reproductive output in marine fishes. pp. 31-61, *In* Early life history and recruitment in fish populations, edited by R.C. Chambers and E.A. Trippel. Chapman and Hall, London.

Tylianakis, J.M., Didham, R.K., Bascompte, J., and Wardle, D.A. 2008. Global change and species interactions in terrestrial ecosystems. Ecol. Lett. 11: 1351-1363.

Urban, M.C., Tewksbury, J.J., and Sheldon, K.S. 2012. On a collision course: competition and dispersal differences create no-analogue communities and cause extinctions during climate change. Proc. R. Soc. B. DOI: 10.1098/rspb.2011.2367

Van der Putten, W. H., de Ruiter, P. C., Bezemer, T. M., Harvey, J. A., Wassen, M., and Wolters, V. 2004. Trophic interactions in a changing world. Basic Appl. Ecol., 5: 487–494.

Van der Putten, W.H., Macel, M., and Visser, M.E. 2010. Predicting species distribution and abundance responses to climate change: why it is essential to include biotic interactions across trophic levels. Phil. Trans. R. Soc. B, 365: 2025-2034.

Vasseur, D.A., and McCann, K. 2005. A mechanistic approach for modeling temperature-dependent consumer-resource dynamics. Am. Nat. 166: 184-198.

Visser, M.E., and Both, C. 2005. Shifts in phenology due to global climate change: the need yardstick. Proc. Roy. Soc. B, 272: 2561–2569.

Vucetich, J.A., Waite, T.A., Qvarnemark, L., and Ibargüen, S. 2000. Review: Population variability and extinction risk. Conserv. Biol. 14: 1704-1714.

Vucic-Pestic, O., Ehnes, R.B., Rall, B.C., and Brose, U. 2011. Warming up the system: higher predator feeding rates but lower energetic efficiencies. Glob. Change Biol., 17: 1301-1310.

Werner, E.E., and Gilliam, J.F., 1984. The ontogenetic niche and species interactions in size-structured populations. Ann. Rev. Ecol. Syst. 15: 393-425

Winder, M., and Schindler, D.E. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology, 85: 2100-2106.

Worm, B., and Myers, R.A. 2003. Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. Ecology 84: 162-173.

Wu, R.S.S. 2002. Hypoxia: from molecular responses to ecosystem responses. Mar. Pollut. Bull., 45: 35–45.

Yang, L.H., and Rudolf, V.H.W. 2010. Phenology, ontogeny and the effects of climate change on the timing of species interactions. Ecol. Lett. 13: 1-10.

Zarnetske, P.L., Skelly, D.K., and Urban, M.C. 2012. Biotic multipliers of climate change. Science 336: 1516-1518.

Chapter 10 Analysis of DFO non-ecosystem services and operations in Atlantic Canada

B.J.W. Greenan*[1] and A. Warburton[2]

[1] Bedford Institute of Oceanography, Fisheries and Oceans Canada, P.O. Box 1006, Dartmouth, NS, B2Y 4A2

[2] Elemental Sustainability, 1673 Barrington St., 2nd Floor Halifax, Nova Scotia B3J 1Z9

* Correspondence: Blair.Greenan@dfo-mpo.gc.ca

Suggested Citation:

Greenan, B.J.W., A. Warburton. 2013. Analysis of DFO non-ecosystem services and operations in Atlantic Canada. Ch. 10 (p. 313–363) *In*: Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin [Shackell, N.L, B.J.W. Greenan, P. Pepin, D. Chabot and A. Warburton (Eds.)]. Can. Manuscr. Rep. Fish. Aquat. Sci. 3012: xvi + 366 p.

10.1 INTRODUCTION

This report summarizes non-ecosystem impacts of climate change to the operations and services of Fisheries and Oceans Canada (DFO), Atlantic. Observed and anticipated impacts are categorized under risk themes that parallel the findings of the 2012 Department of Fisheries and Oceans National Climate Change Risk Profile Update (Interis 2012), and the 2005 precursor report, Climate Change Risk Assessment for Fisheries and Oceans Canada (Interis 2005). The risk themes are:

- Increased Demand to Provide Emergency Response Services,
- Coastal and Marine Infrastructure Damage, and
- Changes in Access and Navigability of Waterways.

Findings from this report will contribute to the Aquatic Climate Change Adaptation Services Program (ACCASP), a national program (starting in fiscal year 2011-2012) to be delivered regionally over the course of five years. The Program objective is to mainstream scientific and socio-economic information about climate change into decision-making processes across departmental sectors. The first step for this program is to get a better understanding of sector risks and vulnerabilities linked to climate change. In response to identified risks and vulnerabilities, ACCASP will carry out ocean science research projects to increase understanding of future climate change and its impacts on ecosystems, infrastructure and operations. The third component of ACCASP is the development of systems and tools for adaptation.

This report contains nine sections. Following the introduction, comment is made about the ranking system used in DFO's ACCASP risk assessment process, as it does not lend itself to dealing with *non-biological* concepts. This challenge is discussed and the approach used to deal with uncertainty for non-ecosystem impacts within this report is described.

Thirdly, climate drivers are examined for projected changes that will directly, or indirectly, impact DFO operations and services. Trends and projections that provide insight to *why* and *where* DFO sectors will be impacted are highlighted. This analysis has taken into consideration the operations and services provided by the following DFO Sectors: the Canadian Coast Guard (CCG), the Small Craft Harbours Directorate (SCH), Real Property Safety and Security (RPSS), and the Canadian Hydrographic Service (CHS).

The fourth, fifth and sixth sections of this report examine the non-ecosystem impacts in more detail, grouped according to risk theme. Rationale to support the inclusion of the impact is provided, and comment is made on the impact's overall impact ranking for decadal and 50-year timeframe.

Impacts are not necessarily negative: they are events (intermittent or progressive) that are changing the circumstances in which DFO operates and provides service. Given the static nature of infrastructure, the impacts from rapid environmental change and intensifying weather events are most often undesirable. However, not all operational changes may be negative. The section, *Potential Opportunities Presented by Climate Change*, outlines anticipated changes to operations and service that could be considered favorable.

A synthesis of expert opinion on observed and anticipated climate-induced impacts to operations and services created an initial list of non-ecosystem impacts for ACCASP. Expert opinion was derived from interviews with personnel and messages and content within internal studies and documents. The eighth section of this report, Expert Opinion, lists personnel interviewed in March 2012, as well as key documents referred to throughout this report. Once an initial list was formed, it was validated using DFO Science climate change trends and projections information. The revised list was then shared with DFO technical experts for feedback and further input, which did indeed result in modifications to impact rankings. Tables 10–22 and 10–23 lists the technical experts who vetted and improved upon the list of non-ecosystem impacts now found in the IVO Summary Table.

The report's last section provides a summary of the non-ecosystem impacts and vulnerability analysis, highlighting priority areas for further research and adaptive action across DFO sectors in the Atlantic Large Aquatic Basin.

10.2 RANKING THE UNCERTAINTY OF NON-ECOSYSTEM IMPACTS

The ACCASP process involved the creation of Impact, Vulnerability and Opportunity summary tables for ecosystem and non-ecosystem impacts. The IVO Summary Tables involve a ranking system for uncertainty that reflects confidence about the inclusion of each particular impact in the IVO Summary Table and estimated degree to which the impact will affect DFO operations and services.

The proposed uncertainty ranking for the IVO Summary Table is based on the extent to which the impact in question has been researched, and the degree to which that research has been peer reviewed. Table 10–1 below illustrates guidelines for levels of uncertainty as adopted from the research of Mandrak, Cudmore and Chapman (2011). In the original research document it is stated, "*These guidelines are intended to provide guidance for conducting detailed-level biological risk assessments in a standardized fashion* (Mandrak et al. 2011)."

Table 10–1 IVO summary table uncertainty ranking

Uncertainty ranking	Description	Illustrative Numeric Range
Very high	Most of the evidence is based on expert opinion and little or no peer-reviewed literature	±90%
High	Evidence is supported by more expert opinion than review information	±70%
Moderate	Evidence is supported by some peer reviewed literature and expert panel opinions	±50%
Low	Evidence is supported by more peer review information than expert opinion	±30%
Very low	Evidence is mostly supported by peer-reviewed scientific information	±10%

Generally speaking, DFO's retrospective assessment of how weather events have affected (or are affecting) operations and services is based on first-hand experience of DFO personnel. The **expert opinion of DFO personnel is the best information available on non-ecosystem impacts of climate change**. The absence of peer-reviewed literature regarding non-ecosystem climate change impacts is understandable: climate-related trends in Department operations or demands for service are not the type of information typically published in peer-review literature.

Because of the binary nature of the proposed guidelines for ranking uncertainty (peer reviewed or expert opinion), non-ecosystem impacts reflect expert opinion almost exclusively. For this reason, the uncertainty rankings for every non-ecosystem impact would be relegated to 'Very High'.

The risk of using the proposed uncertainty ranking (designed for biological risk assessment) for non-ecosystem impacts is that uncertainty rankings will be inappropriately high. The concern being, an inappropriately high ranking could cause a type of potential harm (i.e., loss of life, severe environmental damage) that could be more important (i.e., socially, economically, politically, environmentally) than the probability of its occurrence (Strand and Oughton 2009).

Defining a level of uncertainty around non-ecosystem impacts of climate change is further complicated by the fact that these impacts result from not only the direct effects of climate drivers (e.g., storms and waves, mean sea level rise), but also the indirect effects of changing social constructs (Strand and Oughton 2009). For example, warming air and sea surface temperatures and lessening sea ice extent have contributed to a lengthened boating season. The non-ecosystem implications of more human activity for a greater duration of the year include more demands on SCH infrastructure, and greater potential for search and rescue incidents. Similarly, reductions in ice cover conditions have resulted in increased shipping activity, leading to additional requests for ice breaking services, ice routing information and services, and greater potential for both search and rescue and environmental response incidents.

An initial list of non-ecosystem climate change impacts was developed using primarily first-hand experience: expert opinion of DFO professionals in the Canadian Coast Guard, Small Craft Harbours Directorate, Real Property Safety and Security and the Canadian Hydrographic Service. Those impacts substantiated by research, both peer reviewed and otherwise, were included in the non-ecosystem, ACCASP IVO Summary Table.

In order to determine level of confidence about the inclusion of an impact in the IVO Summary Table, a judgment was made based on the amount and consistency of evidence, and the degree of agreement about that evidence as presented by DFO experts and external research (Mastrandrea et al. 2010).

When discussing potential climate change impacts to infrastructure, expert and scientific resources have to evaluate vulnerability. The definition of vulnerability in this context is defined by the IPCC (2007) as, "*the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, the sensitivity and adaptive capacity of that system.*"

A Small Craft Harbours Climate Change Study involved a literature review to pinpoint those climate drivers most likely to affect SCH infrastructure (Paul MacDonald, pers. comm.). Comment was made about the general nature of predicted impacts, and those impacts are included in the non-ecosystem IVO Summary Table for the Atlantic Large Aquatic Basin. It was not, nor does there exist, a synthesized and detailed assessment of individual asset vulnerabilities. One finding of this process is that SCH and RPSS personnel in the DFO Maritimes Region have developed a Vulnerability Matrix and Climate Change

Custodian Guide (respectively) that, with Departmental support, could be used throughout the Atlantic Basin.

10.3 CLIMATE DRIVERS AFFECTING NON-ECOSYSTEM COMPONENTS OF DFO OPERATIONS AND SERVICES

When evaluating climate change impacts to non-ecosystem components of DFO services and operations, we are hypothesizing how changes in the environment may induce changes in human behaviour and thus alter the demands on DFO services: such as, emergency services, the provision of charts, and ice routing and breaking. Simultaneously, we are also hypothesizing how projected changes in key climate drivers will impact land-based and marine infrastructure, both the infrastructure DFO requires to conduct its operations as well as infrastructure DFO provides to support safe and secure waters, and economically prosperous fisheries and sustainable aquaculture.

This report section highlights changes in climate that are directly and indirectly impacting DFO operations and services. The following section then ties projected climate changes to specific impacts.

10.3.1 Mean Sea Level Rise and Extreme Sea Levels

Mean sea level rise in most of the Atlantic Basin is projected to be higher than global estimates (Yin et al. 2009, Xu and Perrie, 2011). This is in large part due to glacial isostatic adjustment and changes in dynamic sea level (changes stemming from ocean circulation patterns). Indeed, observations confirm this, showing a doubling of global mean sea level rise in certain Atlantic Canada study sites (Forbes et al. 2010). Given these considerations, the potential relative sea level rise in the southern part of the Atlantic basin on the 50-year time scale is 0.3-0.5m (Loder et al., 2013). Recent research about sea level being conducted outside of DFO aligns with DFO Science ACCASP Trends and Projections, including the report by Richards and Daigle (2011) entitled "*Scenarios and Guidance for Adaptation to Climate Change and Sea-Level Rise – NS and PEI Municipalities.*"

There are significant regional differences in mean sea level projections, stemming from the contributions of glacial isostatic adjustment (GIA), regional responses to thermal expansion and land-ice and ice-sheet melt. Sea level in the Atlantic Basin is also influenced by changes in ocean circulation (dynamic sea level), although the understanding and degree of certainty underpinning this factor is relatively low (Han et al. 2012). Comparatively, the certainty surrounding GIA is high (Loder, 2013).

Areas in the southern portion of the Atlantic Basin will experience a greater mean sea level rise than the north. For example, Nova Scotia and the Newfoundland coasts are projected to see a rise of 0.3-0.5 m on a 50-year timescale. However, along the northern Gulf of St. Lawrence coast and the southern Labrador coast the mean sea level is expected to experience a much smaller change because of GIA.

Hence, there is significant spatial variability throughout the Atlantic Basin (Han et al. 2012).

Damage to harbour infrastructure has already occurred due to extreme sea levels and increased wave energy. Extreme sea levels "occur through a combination of the seasonal mean sea level and the largely additive contributions of high tides, surges associated with storms (taken here to include the response to atmospheric pressure as well as wind stress), weekly to interannual changes associated with wind stress and propagating waves, and local effects such as seiches and wave runnup (Loder et al., 2013)."

It is important to keep in mind that most sea level rise estimates do not include the contribution of ice sheet melt. Such a contribution would pose serious consequences to coastal infrastructure in a relatively short time span. As well, if the polar ice sheets show nonlinear and accelerated melting behaviour in the next century, efforts to mitigate sea level rise may be rendered futile (Yin et al. 2012); however, the best understanding of processes governing the Greenland and Antarctic ice sheets does not consider contributions from melting of these to be a major factor in global sea level rise in the next century. Projecting mean sea level requires an understanding of thermal expansion *and* meltwater, and other level-change drivers such as GIA. Therefore, science is not only interested in determining the rate of mean sea level rise, but also figuring out what the anticipated contribution of each driver (e.g., thermal expansion, ice sheet melt, changes in ocean circulation, and GIA) is to that rise. For example, recent research has pointed out that in most Global Circulation Models used to estimate climate changes such as sea level rise, it is possible that ocean heat uptake has been over-estimated (and surface warming has been underestimated), which would in turn affect the accuracy of estimations about the contribution of thermal expansion to sea level rise (Kuhlbrodt et al. 2012). As the understanding of sea level rise components improves, the ability to estimate regional and localized sea level will also improve.

10.3.2 Changes in Ocean Temperature and the Cryosphere

There is a strong link between air temperature, sea surface temperature, and sea ice extent (Han et al. 2012). There is also great seasonal and spatial variation in projected changes in sea surface temperatures (Chassé et al. 2013). These types of changes will alter familiar patterns of ice movement, as well as the extent of ice present. For example, a very pronounced *seasonal* warming is expected in the southern Gulf of St. Lawrence in spring and summer (2026-2046). *Spatially*, the entire western coast of Newfoundland shows a 1-1.5°C warming throughout the year. These findings align with the research of Peterson and Pettipas (2012) that state that extremely low values of sea ice extent were reported off Newfoundland and Labrador for recent years and sea-ice volume in the Gulf of St. Lawrence was at a record-low in 2010. Specifically, trends in the annual mean ice areas for the 1980-2011 period revealed -16%/decade in the Gulf of St. Lawrence, and -20%/decade on the Northeast Newfoundland Shelf (Peterson and Pettipas 2012).

Research about upper-ocean temperatures by Loder et al (2013) indicates it is likely that upper-ocean temperature in winter and summer will increase across most of the Labrador Sea, with the notable exception of off-shelf parts of the subpolar gyre (such as the Labrador Sea), where slight cooling may occur. Further, it is likely that the largest upper-ocean temperature increases in winter will occur in the shelf-slope regions off the Maritime provinces and southern Newfoundland, and that the largest surface temperature increases in summer will occur in these same regions and areas (primarily coastal) to the north that will no longer have ice cover in summer. Specifically, changes in shelf upper ocean temperatures could range from little change in the north (e.g., over the Labrador Shelf) to increases of up to 4 C in the southern Atlantic LAB for the 50-year time scale.

10.3.3 Storms and Waves

Dominant North Atlantic storm tracks will likely shift northward, especially over the northern Northeast Atlantic, where the occurrence of the most intense cyclones increases (minimum sea level pressure below 970hPa or maximum wind speeds equal to or more than 27m/s) (Guo et al. 2012; Jiang and Perrie, 2008, 2006; Yao et al. 2008; Perrie et al., 2010; Long et al., 2009). Whereas the Northeast Atlantic is expected to get both *more* storms and more intense storms, the Northwest Atlantic may experience a small reduction in the total number of cyclones, as well as a slight *decrease* in the most intense storms. That being said, scientists caution that the Canadian Regional Climate Model, and possibly other models "*underestimate the storm track density over the northwest Atlantic area* (Guo et al. 2013)." Comparatively, the mid-latitudes of the North Atlantic are expected to experience a decrease in the number of fall storms in the south, but an increase in the north. The regional models indicate only small changes in the mean wind speeds for the 50-year timeframe.

Climatic factors such as storminess and cyclone intensities and trajectories drive changes in the wave environment: storms in particular are a generating force behind wave fields. Changes in storm activity and atmospheric circulation are a primary driver of changes in wave climate, resulting in the finding that waves will intensify in the northeast Atlantic and southwest North Atlantic (Guo et al. 2013). This is related to the finding that North Atlantic storm tracks are projected to shift northward, particularly in the winter and fall in the 50-year timeframe (Perrie et al. 2013; Guo et al. 2013)). Trends and projections have suggested the significant wave height will likely show small decreases in the summer period.

Reduction of sea ice and an increasing mean sea level can also influence localized wave height. The ACCASP climate change trends and projections report found that "*reduced ice cover and reduced periods of ice cover in the Gulf of St. Lawrence, Newfoundland and Labrador and Baffin-Davis regions*" will likely cause substantial increase in wave height (Loder et al., 2013). Increasing exposure, and thus vulnerability to waves is exacerbated by the fact that the lack of ice can also increase wave runnup.

10.3.4 Air and Sea Surface Temperature Changes

In the context of this report, the most significant aspect of air and surface water temperature is its influence on the presence of ice. Air temperature (which appears to be a reliable proxy for sea surface temperature in the Gulf of St. Lawrence) seems to influence the presence / extent of sea ice. As explained by Galbraith and Larouche (2013): "*Updated comparisons show that winter air temperature anomalies of +2°C account for all three almost ice-free winters recorded in the Gulf of St. Lawrence (1969, 2010 and 2011), a situation that could become normal by the end of this century if air temperature warming trends are maintained.*"

Winter air temperature changes are expected to be slightly greater than summer air temperature changes over most of the Atlantic Basin, with greater degrees of change in the Labrador region (Loder at al., 2013). The long-term air temperature warming trends are typically in the range of 0.5 to 2 C per century. This affects trends in seasonality: for each degree of air temperature warming, the onset of summer is 0.9 to 1.4 weeks earlier. For future projections on the 50-year timeframe, it is very likely that air temperature will increase in all regions of the Atlantic LAB in all seasons. It is likely that annual mean air temperature will increase by 2-3.5 C in Scotian Shelf-Gulf of Maine and Gulf of St.Lawrence, and by 1-3 C in the Newfoundland-Labrador Shelf region.

Another important aspect of changing surface water and deep-water temperatures is the possible impact on aquatic species. Changing temperatures, and possibly changes in circulation, will influence the habitability of any given area for particular species. From the context of non-ecosystem impacts, the relationship is one of having to provide services to fisheries, and connecting the presence or movement of pursued stocks to changes in fishing activity (i.e., where fishing vessels go, when and for how long).

10.3.5 Ocean and Coastal Circulation Patterns

For the Atlantic Basin, there are potential changes in local and regional circulation due to changes in freshwater run-off, winds, coastal fronts and large-scale circulation. A possible example of the impact of large-scale circulation changes would be changes in circulation on the Scotian Shelf if the subtropical gyre moved northward shifting the Gulf Stream closer to the shelf break; this would strongly influence shelf-slope exchanges of water. However, such changes are poorly understood at this point and, therefore, highly uncertain.

10.3.6 Erosion

Coastal erosion is a consequence of climatic and anthropogenic factors (e.g., land use, presence and type of coastal infrastructure) interacting with coastal geology. Much of the coastline in the Atlantic Basin features sedimentary rocks (e.g., gypsum, shale, limestone) or unconsolidated sediment: all of which are highly erodible by the forces of wind, coastal waves and currents, and increasing water levels. Rising sea levels are beginning to overtop (rise above) bedrock: reaching up to vulnerable surficial materials. In time, erosion of surficial material steepens slopes, which increases the risk of slope collapse (i.e., segments of land/rock breaking away or flowing down). As well, sea level rise in combination with wave energy is working away at sedimentary layers at sea level, where igneous and metamorphic rocks are layered on top. While this creates interesting sea caves and pockets along the coast, as those hollows become larger the ground above loses its support and there is eventual collapse.

Rising sea level is not the only climate driver in action. Increased numbers of short intense rainfalls (and increasing storm surge levels) serve to saturate coastal materials such as clay. Once saturated, the clay flows. The movement of material is also triggered by freeze-thaw cycles, which are projected to increase in Atlantic Canada (Williams and Richards 2011).

The trends of rising sea level and decreasing ice cover combine to amplify the effect of wave energy. Localized land features and bathymetry also influence vulnerability to erosion. For example, as the sea level rises, the wave breaking action of shoals will diminish, thus allowing more wave energy to impact the coast. Similarly, the erosion-mitigating role of barrier beaches and wetlands lessens as sea level rises. As waves and other climate drivers erode the coast, coastal assets become further exposed to sea level rise and wave energy.

According to Garth Dumont, a professional Geoscientist with Nova Scotia Department of Natural Resources and mineral resource consultant throughout Atlantic Canada, erosion rates could easily double where sedimentary rocks are present (pers. comm.).

10.4 INCREASED DEMAND TO PROVIDE EMERGENCY RESPONSE SERVICES

Climate change impacts to emergency response services include:

- Environmental Response Services
- Search and Rescue Services

The climate change impacts to emergency response services listed in the non-ecosystem IVO Summary Table are listed in the table below (Table 10–2).

Table 10–2 Emergency response impacts listed in IVO summary table.

Climate Change Impact	Time-frame	Impact Severity	Probability	Uncertainty
Increased demand for environmental response in relation to winds, waves and storms and disappearing sea ice	decadal	Medium	Moderate	Moderate
	50-yr	Medium	Moderate	Moderate
Increased demand for search and rescue services in relation to changes in sea ice, waves and winds and storms	decadal	Medium	Moderate	Moderate
	50-yr	Medium	Moderate	Moderate

Climate Change Impact	Time-frame	Impact Severity	Probability	Uncertainty
Increased need to update/inform Joint Rescue Coordination Centre Risk assessment models (used to identify areas of vulnerability, and inform deployment of personnel and equipment) on trends for winds/storms, waves and sea ice	decadal	Low	Unlikely	Moderate
	50-yr	Low	Moderate	Moderate

10.4.1 Emergency Response—increased Demand for Environmental Response

Table 10–3 Emergency response services—Increased demand for environmental response

Impact	Increased demand for environmental response in relation to winds, waves and storms and disappearing sea ice		
	Impact severity	Probability	Uncertainty
decadal	Medium	Moderate	Moderate
50-yr	Medium	Moderate	Moderate

10.4.1.1 Rationale

The potential for an increased demand for environmental response was identified in the 2005 Climate Change Risk Assessment for Fisheries and Oceans Canada, and again in the 2012 Update, National Climate Change Risk Profile (the 2012 Update). The 2012 Update listed this impact as: increased frequency and/or severity of marine spills and bilge water disposal and associated costs due to intensified winds and storms and disappearing sea ice.

An increase in the number of environmental response incidents was listed as a climate change impact in an internal DFO Climate Change Questionnaire in 2009. The questionnaire sought to learn: how aware the sector's understanding was of climate change in terms of trends and impacts; what the affects of those impacts are on operations; perceived level of adaptive capacity with the sector; degree to which climate change affects daily operations; desire for additional climate-related information; immediate and anticipated climate-induced risk; current initiatives (if any) to mitigate climate-induced risk; and sources of climate information.

The CCG Maritimes Region Environmental Scan (2011) listed longer boating/shipping seasons because of favourable weather and ice conditions as a climate change impact, making an indirect link to predicted increases in demand for emergency services.

This impact was also a point of discussion recorded in the meeting minutes from the Initial ACCASP Regional Meeting in the Maritimes Region: December 9, 2011. The minutes captured the statement, "*More frequent and extreme weather events could imperil safety of sea going delivery of fuels by tankers as well as damage to shore infrastructure used to transport or contain hydrocarbons and chemicals. Increased intensity and frequency of storms could damage ships with dangerous and/or volatile cargos that may require port of refuge.*" This impact was further validated during interviews with Coast Guard Personnel throughout the Atlantic Basin in March 2012.

DFO Technical Reports substantiate changes in the marine environment that could precipitate more environmental incidents. The climate drivers of concern are: warming air and sea surface temperatures, waves and storms, and changes in ice extent and movement. The lessening extent of sea ice (thanks to warmer air and sea surface temperatures) in combination with longer ice-free periods in most of the Atlantic Basin is believed to be a significant driver behind increased marine traffic. That being said, socio-economic and political constructs could be argued to play just as a significant role as climate change in the increasing risk associated with environmental spills (intentional and otherwise) and demands on environmental response services.

10.4.1.2 Level of Risk

The Risk underpinning this impact is that DFO will not have the capacity to adequately mitigate environmental incidents. For both the decadal and the 50-year timeline the level of Risk (impact ranking) to operations and services is Medium for the following reason.

DFO personnel are witnessing an increase in the volume of Marine traffic in the Atlantic Basin, and with this is an inherent increase in risk of emergency situations. The environmental impact of any one spill or cumulative spills can be extreme, but that is not in question here. The question is, what is the risk of an increasing number of environmental incidents on DFO operations and services? Given the current resource strains in the CCG, both in terms of budget capacity and marine infrastructure, the likelihood that CCG could respond to an increasing number of calls *without* making sacrifices to the provision of other services is small. As well, the fact that environmental incidents may occur further from responding stations given the changing nature of the seascape increases the challenges to resources and response times.

In conjunction with disappearing sea ice presenting new opportunities for access / travel, economic, technical and political influences are driving an increase in marine traffic in emerging routes. This is unlikely to change. As well, there is uncertainty about the design and capacity of privately owned, international vessels to handle the future marine environment. For these reasons, the level of probability is moderate for both timeframes (i.e., has occurred before, or has been observed in similar circumstances).

The uncertainty associated with this ranking is Moderate. There is low uncertainty that the volume of marine traffic will increase and with it an inherent risk of environmental spills. Again, this is due in large part to disappearing sea ice and emerging routes, the possible introduction of new harbours and a potentially lengthened shipping season. However, the science about winds and storms also has uncertainty. For this reason, the uncertainty ranking for this impact is moderate: respectful of both certainty in the reduction of sea ice extent, and *uncertainty* in projections related to storm activity.

10.4.2 Emergency Response Services—Increased Demand for Search and Rescue

Table 10–4 Emergency response services—Increased demand for search and rescue

Impact	Increased demand for search and rescue services in relation to changes in sea ice and winds and storms		
	Impact severity	Probability	Uncertainty
decadal	Medium	Moderate	Moderate
50-yr	Medium	Moderate	Moderate

10.4.2.1 Rationale

The CCG is seeing more marine traffic, with activity during a greater portion of the year, stretching into a larger geographic area. Whether the impetus be anthropogenic climate change, natural variability or an interplay of the two, mariners are entering new areas and experiencing unexpected challenges such as: storms, winds and waves; out-dated or absent charts; changes in ice extent and movement. As well, CCG personnel expressed concern that mariners are unaware of the inherent risks of the changing marine environment, and under-appreciate the fact that environmental response and search and rescue operations also face increasingly difficult situations, including the increasing distances of incidents from shore.

The potential for an increased demand for Search and Rescue Services was identified in the 2005 Climate Change Risk Assessment for Fisheries and Oceans Canada, and again in the 2012 Update, National Climate Change Risk Profile. The 2012 update stated, "*The absence of sea ice creates conditions where wave height can be more severe than historical conditions, leaving mariners unprepared and in need of emergency response* (Interis 2012)." The Update also said, "*Increased vessel traffic in uncharted or poorly charted areas may result in incidents where emergency response is required* (Interis 2012)."

Other closely related impacts in the 2012 Update need highlighting, as they have not been treated as separate impacts within this report, but are of serious concern:

- Increased difficulty and risk of personal injury or loss of life during rescue missions under extreme conditions: storms and waves.

- Inability of small Northern communities to provide respite housing and other necessities of life for a large number of people in events of emergency incidents triggered by storms and waves.
- Increased cost of communications to mariners about the need to travel with extensive supplies of necessities due to potentially longer response times to marine emergencies.
- Increased legal costs due to increased suits related to emergency response.
- Reduced support for research activities, due to re-deployment of vessels to emergency response activities (Interis 2012).

Increased demand for search and rescue services was also highlighted in the internal DFO Climate Change Questionnaire in 2009. The question posed was, "*How do you expect climate change to impact your sector?*" This impact was also mentioned during seven interviews with Coast Guard Personnel throughout the Atlantic Basin in March 2012.

The **concern that DFO will not be able to accommodate an increased demand for Search and Rescue services** was also mentioned in an internal Coast Guard PowerPoint deck titled, Climate Change Forum: CCG Maritimes Region (2010), listing operational challenges exacerbated or introduced by climate change trends: specifically, rising sea levels, melting of ice, severe weather changes, and changes in ocean currents. Atmospheric and ocean temperature changes were acknowledged for the role they play in fish range and health, which relates to boating and fishing seasons and in turn indirectly affects CCG's emergency response services.

Interestingly, there is an impression within the CCG that severe weather will be exacerbated in both intensity and *frequency*. However, only in the Northeast Atlantic is frequency expected to increase. The Northwest Atlantic may experience a small reduction in the total number of cyclones as well as a slight decrease in the most intense storms. The idea that frequency will increase came up in the in the PowerPoint deck titled, CCG Maritimes Region Environmental Scan (March 2011), where three of the five identified links between climate change impacts and CCG programs and services were:

- longer boating/shipping seasons because of favourable weather and ice condition,
- increase in weather-related SAR and ER incidents because of more frequent storms and because of the lengthened boating/shipping seasons, and
- increase in humanitarian relief efforts (CCG 2011).

The potential for an increased demand for search and rescue services was also a point of discussion recorded in the meeting minutes from the Initial ACCASP Regional Meeting in the Maritimes Region: December 9, 2011. The meeting minutes summarized discussion points of client sectors regarding currently observed impacts, resulting demands to change operations, and expectations for

ACCASP products. Within those minutes it is stated, "*The frequency and intensity of weather events will generate more Search and Rescue events.*"

DFO Technical Reports substantiate the concern that the demand for search and rescue services could increase. Trends for increasing air temperatures and sea surface temperatures, which influence many fish stocks and extent of sea ice, combine to create favourable conditions for more sea travel: including, shipping, mining and exploration, fishing and recreational. Additionally, according to Galbraith and Larouche (2013), "*summertime conditions could be extended by as much as two weeks with an overall increase in air temperature of 1 C* (2012)." In fact, seasonality trends indicate that for every degree of air temperature increase, we may expect summer onset 0.9–1.4 weeks earlier. The long-term air temperature warming trends are typically in the range of 0.5 to 2°C per century. Indeed, the CCG is seeing more marine traffic, and activity during a greater portion of the year and stretching into a larger geographic area.

Whether the impetus be anthropogenic climate change, natural variability or an interplay of the two, mariners are entering new areas and experiencing unexpected challenges such as: waves and storms; out-dated or absent charts; and changes in ice extent and movement.

As mentioned previously, one of the impacts to CCG operations and services is an increased need, and cost for communicating to mariners about the need to travel with extensive supplies of food and water because of the long response time (and potential increase in that response time) to marine emergencies. CCG personnel expressed significant concern that mariners are unaware of the inherent risks of the changing marine environment, and under-appreciate the fact that environmental response and search and rescue operations also face increasingly difficult situations.

10.4.2.2 Level of Risk

The risk underpinning this impact is that DFO will not have the capacity to adequately respond to search and rescue calls. For both the decadal and the 50-year timeline the level of risk (impact ranking) to operations and services is Medium.

This impact is considered Medium, but could arguably be ranked higher. DFO personnel perceive an increase in the volume of Marine traffic in the Atlantic Basin, and with this is an inherent increase in risk of emergency situations. The social impact of marine accidents is not to be taken lightly: indeed, the seriousness of marine accidents is not in question. **What *is* in question is, what is the impact of an increasing number of search and rescue calls to DFO operations and services?**

Given the current resource strains in the CCG, both in terms of budget capacity and the age and state of marine infrastructure, the likelihood that CCG could respond to an increasing number of calls *without* making sacrifices to other services is small. As well, the fact that incidents may occur further from responding stations given the changing nature of the seascape increases the challenges to resources and response times. One could argue that a long-term realignment of financial resources is needed to better position CCG's capacity to respond to emergency situations, and therefore should be ranked as having a fairly high impact. However, protocols for response are well established and the continuation of outstanding efforts of DFO personnel involved in search and rescue operations is *not* dependent on a Departmental re-alignment of operations or objectives. Therefore, the impact ranking is Medium, not higher.

The level of probability is Moderate for both timeframes. The probability ranking takes into consideration two hypotheses: first, the volume of marine traffic will continue to increase with time (e.g., more mining, emerging routes, potential revitalization of select fisheries). Secondly, changes in the marine climate may impose more risk.

Probability rankings were withheld from being higher because multiple, human behaviour variables at play, not just the climate-induced reduction in sea ice. Economic, technical and political influences are driving an increase in traffic. As well, marine accidents are seldom solely triggered by a weather event. Human judgments are also involved. While trends and projections indicate that sea ice in this LAB is very likely to decrease in the future, the existing scientific evidence does not indicate a significant change in storm frequency or intensity. However, in areas such as the Gulf of St. Lawrence and Newfoundland Shelf the reduction in Winter sea ice could translate into more hazardous conditions, as waves will be present in areas previously covered with sea ice during that period.

There is Moderate uncertainty underpinning the rankings for this impact. While an increase in search and rescue incidents would undoubtedly place additional strain on CCG finances, infrastructure and equipment, and personnel, the degree to which winds, waves and storms will exacerbate the number of search and rescue calls is very uncertain. Thus, a moderate ranking reflects a compromise of complex, interrelated factors.

10.4.3 Emergency Response Services—Joint Rescue Coordination Centre

Table 10–5 Emergency response services—Joint Rescue Coordination Centre

Impact	Increased need to update/inform Joint Rescue Coordination Centre Risk assessment models (used to identify areas of vulnerability, and inform deployment of personnel and equipment) on trends winds/waves/storms and sea ice		
	Impact severity	Probability	Uncertainty
decadal	Low	Unlikely	Moderate
50-yr	Low	Moderate	Moderate

10.4.3.1 Rationale

The Joint Rescue Coordination Centre (JRCC) currently uses risk assessment models to identify areas of vulnerability. These models are used to strategically deploy personnel and equipment. Data explaining how weather patterns are changing would be valuable input to their existing risk models and enhance JRCC's long range planning efforts. For example, general information on climate trends and projections could help predict areas of future increased use and related risk vulnerability. This information would be valuable for budgeting in that it would inform anticipated deployment of both resources and personnel in relation to new patterns of mariner behaviour.

The March 2012 interviews with four DFO sectors regarding their level of risk to climate change hazards and impacts, revealed the potential need to update the Joint Rescue Coordination Centre Risk assessment model with current climate science. Harvey Vardy, Acting Superintendent Search and Rescue from the JRCC confirmed that this group could use climate trends information to support their operations. He noted that there is definite evidence of changes in waterways, with more vessels entering Northern waters and staying longer. This information is tracked, but such changing movement has not been attributed to climate change in any definitive way.

10.4.3.2 Level of Risk

What is the level of response required from the Department to manage and mitigate the challenges of keeping the JRCC Risk Assessment Model as effective as possible? As was the case with the Distribution and Drift Models used for emergency response, the key risk associated with this impact is that environmental data will not be available, will be out of date, or simply incorrect.

With this in mind, the impact was ranked as Low for both timeframes, meaning 'consequences can be absorbed, but management is needed to mitigate impact.' This being said, it needs to be pointed out that a Low ranking assumes that DFO Science will be well-enough funded in the future to maintain up-to-date climate data relevant to the Model.

It is Unlikely that the challenge of incorporating climate trends and projections into the Risk Model will have a significant affect to operations and services in the short-term (i.e.,, decadal timeframe). However, the challenge and importance of maintaining a robust process of environmental data transfer into the Risk Model will elevate with time. A Moderate ranking of probability was given for the 50-year timeframe due to concerns about both adequate funding for DFO Science in the future, as well as the potential for accelerated changes in climate.

There is Moderate uncertainty for this impact. Changing climate drivers will require constant monitoring, and up-to-date data must be continually and effectively transferred into the Risk Assessment Model. That being said, the level of scientific certainty behind estimates for climate change for winds, waves, storms and ocean circulation is relatively weak. Therefore, the rate at which these climate drivers will change and potentially impede the accuracy of the Model is less certain.

10.5. COASTAL AND MARINE INFRASTRUCTURE

Climate change impacts to DFO coastal infrastructure include:

- Harbour infrastructure and access to harbour infrastructure
- (SCH, RPSS and CCG assets located in harbours)
- Coastal Infrastructure
- (CCG and RPSS assets not located in harbours)
- Floating Navigational Aids

The climate change impacts to infrastructure listed in the IVO Summary Table are listed in the table below (Table 10–6).

Table 10–6 Coastal infrastructure impacts listed in IVO summary table

Climate Change Impact	Time-frame	Impact Severity	Probability	Uncertainty
Coastal infrastructure (CCG, SCH and RPSS assets) will need to be updated as mean sea level, extreme sea level and winds, waves and storms compromise the design capacity and structural integrity of assets	decadal	Very high	Almost certain	Low
	50-yr	Very high	Almost certain	Very low
Harbour infrastructure will need to be adapted for changes in use prompted by temperature changes and ecosystem trends	decadal	Very high	Moderate	Moderate
	50-yr	Very high	Likely	Low
Increased maintenance costs due to greater biological activity of undesirable aquatic plants and animals associated with increased air and surface water temperatures, and decreased salinity	decadal	Medium	Moderate	Low
	50-yr	Medium	Likely	Low
Harbour infrastructure (SCH and RPSS assets) increasingly vulnerable to significant and costly structural damage from ice rafting and ice pile up due to sea ice changes	decadal	Medium	Moderate	High
	50-yr	Medium	Moderate	High
Coastal infrastructure (SCH, CCG and RPSS assets) and	decadal	Very high	Almost certain	Low

Climate Change Impact	Time-frame	Impact Severity	Probability	Uncertainty
access to coastal infrastructure compromised by rapid coastal erosion	50-yr	Very high	Almost certain	Low
Increased need to repair, relocate or replace floating navigational aids due to winds, waves and storms	decadal	Medium	Moderate	High
	50-yr	Medium	Moderate	High
Increased costs associated with increased vessel operational requirements and modifications to meet changing needs due to changing sea ice, storms and winds, and waves	decadal	Very high	Almost certain	Moderate
	50-yr	Very high	Almost certain	Moderate

10.5.1 Comments on Coastal Exposure

RPSS recognizes that their greatest level of overall risk results from the age of DFO infrastructure. In a DFO Climate Change Adaptation Program Client-Needs Workshop (December 2011), the following information was presented:

- Annual funding required to keep core harbours in good working condition based on life cycle management principles has been estimated at over $135M.
- Current budget for repair and maintenance projects is ~$70M annually, including ~$10M for dredging.
- Facilities in poor condition are more vulnerable to climate change damage.

Concerns about maintaining aged infrastructure are heightened by observed and anticipated changes in climatic effects. There is a recognized need for information that could assist in assessing how risk vulnerable these assets are. To date, there is no record of climate change related risks per site, or resulting prioritization of assets requiring adaptive measures.

Although the natural features of some harbours may mitigate exposure to climate impacts such as wind and waves, all coastal and floating infrastructure—whether in a sheltering harbour or not—is subject to the affects of a changing marine environment.

DFO properties are categorized into seven different groups based on function and usage. As an example of the breadth of DFO coastal assets, a Maritimes/Gulf regional inventory with categorical definitions is shown below, as of November 2007. Note that this inventory does not include assets in Quebec and Newfoundland and Labrador. RPSS Maritimes provides mandatory services for all Category 1, 2 AND 3 sites and some Category 4 and 6 sites. RPSS also offers optional services to other categorical sites, and select facilities outside of their home region as required.

Table 10–7 RPSS Inventory in Maritimes and Gulf

RPSS Inventory		Maritimes	Gulf	Total
Category 1	Major facilities such as laboratories, Coast Guard bases, warehouses and office facilities	23	39	62
Category 2	Minor facilities such as Light Stations, Search and Rescue (SARS), Fisheries Offices and Facilities (Camps and Camp Sites), and Marine Communication and Traffic Services (MCTS) stations	91	55	146
Category 3	Vacant Land	37	7	44
Category 4	Land based infrastructure such as transmission lines, telecommunication sites, telecommunication towers mainly under the custodianship of CCG and hatcheries under the responsibility of Real Property			
Category 5	Marine Navigation sites	411	460	871
Category 6	Marine based infrastructure such as breakwaters, waterways,	20	9	29
	fish-ways, channels, wharves and ladders			
Category 7	Small Craft Harbours	335		335
Total		938	573	1511

10.5.2 Coastal Infrastructure–Design Capacity and Structural Integrity Compromised

Table 10–8 Coastal infrastructure–design capacity and structural integrity compromised

Impact	Coastal infrastructure (CCG, SCH and RPSS assets) will need to be updated as mean sea level, extreme sea level, winds, waves and storms compromise the design capacity and structural integrity of assets		
	Impact severity	Probability	Uncertainty
decadal	Very high	Almost certain	Low
50-yr	Very high	Almost certain	Very low

10.5.2.1 Rationale

The 2005 Fisheries and Oceans Climate Change Risk Assessment Report listed the following effects of climate change to infrastructure:

- Increased incidence of storm surges, extreme weather events and associated wave energy, such as larger waves and possibly higher storm surges can directly damage infrastructure, particularly those already in poor condition.
- Sea level rise in some regions (Nova Scotia and PEI, Magdalen Islands, southeastern New Brunswick and Newfoundland, and the western Beaufort coast) can lead to the need to adjust infrastructure, and can exacerbate the effect of increased wave energy.
- Fluctuating water levels and extreme waves could increase the requirement to adjust wharves, breakwaters and shoreline protection (Interis 2005).

The impacts listed above were repeated in the 2012 Climate Change Risk Profile: a National Update to the 2005 report. It was also noted that, "*Infrastructure planning that considers climate change will require a longer-term strategic perspective and may necessitate up-front investments in more robust infrastructure* (Interis 2012)." As well, "*SCH, in collaboration with Public Works and Government Services Canada and Harbour Authorities, reacts promptly to rectify infrastructure damage after storms, within available resources. However, an increased frequency of severe weather damage may strain resource allocations and result in delayed response times* (Interis 2012)."

DFO Science research about climate change trends and projections suggests that there is mixed information on recent changes in winds for the Atlantic LAB. Satellite altimetry data from the past two decades indicate a general increase in 100-year extreme wind speeds in the northwest Atlantic. Other analyses indicate small or no changes in mean wind speeds. Changes over next decade are uncertain and may be dominated by unpredictable natural variability. While the perception in other DFO sectors appears to be that there is an increased frequency of severe weather, the existing data does not seem to support that the *number* of events has increased. It may be that other complicating factors has made infrastructure more susceptible to damage, and that the *intensity* of storms is shifting.

On the 50-year timescale, storm tracks are expected to shift northward. This will result in decreased number of fall storms in the southern part of the LAB but an increase in the north (Guo et al. 2013a). Regional models indicate only minimal changes in average wind speeds.

Concerns about sea level rise are substantiated by current research both within, and outside of DFO. For example, Batterson and Liverman (2010) of Newfoundland and Labrador's Department of Natural Resources estimated sea-level change leading up to 2050 and 2100 for four zones covering the province. In their findings they report that areas of the province prone to coastal flooding and erosion will be severely impacted over the next century. As well, areas expected to flood with a 100-year recurrence interval currently will likely flood once every twenty years or less.

DFO Science research indicates that the present rates of sea level rise range between -0.6 and 3.6 mm/year at tide gauge stations in the Atlantic region. Using these trends to project forward to mid-century, the frequency of flooding events will increase and the return period will be reduced by a factor of 3 to 6 in the Gulf of Maine. This means that a weather event that presently only happens on average once every 50 years will happen once every 16 to 9 years. The frequency of flooding events will increase by a factor of 5 along the Nova Scotia's coast, and by a factor up to 2 in the St. Lawrence Estuary. It should be noted that the frequency of flooding events will be reduced slightly in Quebec City by a factor of 0.82, because of the fall in mean sea level caused by the rise of land masses. These estimates are lower bounds in most cases because they do not take into consideration the impact that reduced sea ice in the winter would have on extreme sea level.

SCH commissioned the *Small Craft Harbours Climate Change Study* (AMEC 2011) to better understand climate change induced risks, vulnerabilities and opportunities on commercial fishing harbours. Harbour infrastructure of concern includes: fixed wharfs, floating wharfs, shore protection and breakwaters. **The two climate change impacts deemed to have the highest impact on SCH in eastern Canada are relative sea level rise and increased storm activity, with associated storm surge and wave energy**.

The CCG's Maritimes Region Environmental Scan (March 2011) highlighted likely impacts of climate change on CCG programs and services, including, '*increased infrastructure damage to coastal assets such as fixed aids and Search and Rescue lifeboat stations*.' Other civil marine infrastructure at significant risk includes but is not limited to: towers, lighthouses, range lights, breakwaters and repeater stations.

A DFO Climate Change Adaptation Program Client-Needs Workshop held in December 2011, reiterated risks identified in the National Risk Profile and the SCH Climate Change Study (AMEC 2011). Specifically, the workshop discussed: infrastructure destruction, damage or reduced life, and harbour re-location requirements. In both cases, the concerns relate to increasing program costs, and reduced or interrupted service levels. The Client-Needs Workshop also identified knowledge gaps: areas in need of further research. One such knowledge gap dealt with predicted water level changes for the Gulf of St. Lawrence and the Labrador Sea.

The 2012 interviews with SCH personnel brought to light concerns about the cumulative and compound effects of climate change. For example, while the Sector has a general understanding of sea level rise (i.e.,, at a coarse scale and based on information in the public domain), they are less sure of how sea level projections may affect infrastructure when combined with storm surge and rapid ice breakup. Where might this be of greatest concern, to what degree and when? Another example of compounded uncertainty involves changes in relative sea level combined with projected changes in tide levels, especially in the Bay of Fundy.

The 2012 interviews also gave SCH personnel the opportunity to explain that any science model that provides an estimate on the anticipated marine environment (encompassing multiple climate elements and indices) will be used to strategically plan for the design of SCH's harbour system. Paul MacDonald, an Environmental and Safety Engineer with SCH-Maritimes, pointed out that the *timing* with which certain impacts are expected to be experienced is of particular interest (pers. comm.). Harbours, for example, have an approximate life span of 50 years. SCH will need to accommodate existing sea level conditions as they invest in harbour refurbishments, while simultaneously planning for how existing or new infrastructure can be designed to adapt to changing water heights and associated storm surges.

Xu and Perrie (2011) provide insight into the complexity, and the importance of localized wave modeling to inform vulnerability of harbour-front assets. The good news is that this research demonstrated that the forecast system consisting of the waves, winds, water depth and storm surge components can lead to reliable forecasts of water levels (Xu et al. 2011). The application of such work can inform the design and construction of coastal assets (e.g., harbours, slipways, footings for range lights etc.) and land use planning and development bylaws for the protection of people and property.

M. Stéphane Dumont, Regional Engineer-Quebec, highlighted the need to downscale models projecting the nature and activity of ice, sediment transport, wind, waves and tides, to specific areas where the presence of SCH assets is dense (pers. comm.). Existing climate models do not convey climate effects at a scale fine enough for SCH properties to assess current and future risk vulnerability in a meaningful way. Specifically, studies need to focus on the Chaleur Bay (area of significant weather-related damage in 2010) and extend to Tadoussac along the St. Lawrence River. Similarly, research regarding sedimentation transport should be focused where the need for dredging is already high and is noticeably intensifying. Madeleine Islands is one such place. SCH has indicated that there are additional sites within Quebec and New Brunswick where sedimentation is a grave concern.

Overtopping and flooding of coastal infrastructure is already impeding operations and endangering personnel, as well as highlighting two critical policy issues: lack of capacity to address damaged infrastructure, and lack of capacity to conduct formal inspections. For example, there are numerous wharves that were damaged by severe weather (some as long as 10 years ago) which have not been repaired and are now officially and formally deemed unsafe for use, such as the wharf at L'Institut Maurice-Lamontagne (pers. comm.). Unfortunately, there is no budget to support formal inspections, so there are other wharves that some mariners *know* are unsafe but have not been formally recognized as such.

It should be noted that while this impact is addressing coastal infrastructure, hurricanes and tropical storms that pass through our region could affect inland facilities and resources as well. While impacts to inland infrastructure were not highlighted in the non-ecosystem IVO Summary Table, weather-related damage to inland assets *can* undermine the Department's financial and functional ability to maintain normal operating conditions and levels of service.

10.5.2.2 Level of Risk

Given the overall age of much of the Department's coastal infrastructure and thus its resilience to weather-related damage, and the sheer number of coastal assets in question, the impact ranking assigned is Very High for both time frames. That being said, within the 50-year timeframe, a significant number of assets will reach or surpass their life expectancy. As well, during this timeframe they will have been exposed to increasing mean and extreme sea level, waves, storm surge, erosion, and possibly rainfall events. Substantial financial, technical and human resources will be needed to maintain, relocate or replace coastal infrastructure and resources allocated for the provision of Critical Services.

The continued pursuit of the Department's strategic outcomes (Safe and Secure Waterways, Economically Prosperous Maritime Sectors and Fisheries, and Sustainable Aquatic Ecosystems) may require a large-scale, long-term financial commitment, *but* can be achieved 'with proper management', as framed by IVO Summary Table criteria for ranking impact level.

Mr. Robert MacDonald of RPSS Maritimes noted that, "RPSS wharves (in comparison to SCH assets) are generally found at major sites and accommodate CCG vessels (pers. comm.)." Mr. MacDonald also pointed out that, "present-day wharf projects are designed with sea level rise and associated storm surge and wave impacts in mind (pers. comm.)." Therefore, the SCH sector may be more impacted than RPSS. Another interesting point made by Mr. MacDonald is that "light-stations owned by RPSS have been declared surplus under the Heritage Lighthouse Protection Act, and any that stay in (their) inventory will be replaced by steel towers if impacted by sea level rise (pers. comm.)."

The probability associated with this impact is Almost Certain for both time frames. There is high agreement of DFO personnel about the state of coastal infrastructure overall, and great respect for localized knowledge of specific assets. The fact that some coastal infrastructure is increasingly inadequate, or even presently unsafe, is well known: analogous to the concept of 'occurring regularly' as a weighting factor in the IVO Summary Table's probability ranking scheme. Similarly, there is no disagreement amongst DFO that maintaining coastal infrastructure will require significant effort. For this reason the uncertainty level is Low for the decadal period, and Very Low for the 50-year timeframe: the idea being that the financial severity of this impact on existing infrastructure will increase with time.

Experts in RPSS, SCH and CCG are currently trying to focus their infrastructure efforts on conducting site/asset specific vulnerability analyses and prioritizing actions.

10.5.2.3 Projected changes in freeze-thaw cycles could add stress

While the above-mentioned climate impact focuses on the climate drivers of mean sea level, extreme sea level, and storms/ winds/waves, projected changes in freeze-thaw cycles will also have an affect on coastal infrastructure. Deterioration of the built environment induced by the passing of air temperature through the melting point will serve to introduce or aggravate infrastructure's poor state of repair. With the majority of coastal infrastructure already being aged, changes in freeze-thaw cycles are an unwelcomed additional structural and financial stress.

It should be noted that while the number of annual freeze-thaw cycles is projected to decrease in the Maritimes due to a warming climate, the number of freeze-thaw cycles in winter is expected to stay nearly the same or increase (Richards et al., 2012). At this time of year, repeating freeze-thaw cycles do the most damage.

10.5.3 Coastal Infrastructure—Need to Adapt Harbour Infrastructure

Table 10–9 Coastal infrastructure—Need to be adapt harbour infrastructure

Impact	Harbour infrastructure will need to be adapted for changes in use prompted by temperature changes and ecosystem trends		
	Impact severity	Probability	Uncertainty
decadal	Very high	Moderate	Moderate
50-yr	Very high	Likely	Low

10.5.3.1 Rationale

A key factor influencing marine traffic is how fish stocks will respond to their changing environment: changes in water temperature and /or circulation patterns, and related changes in food supply and predation. Although "species reorganization and displacement" (risk 3 in the 2012 National Risk Profile) is categorized as an ecosystem impact, there are non-ecosystem repercussions: "SCH may need to be adapted (re-located) to adjust to fish stock re-distribution and ensure that SCH continues to meet needs of the changing commercial fishing and aquaculture industry (Interis 2005)."

Paul MacDonald (SCH-Maritimes) gives the example that if increasing water temperatures cause temperate-water species such as lobster and cold-water species such as snow crab and shrimp to migrate to colder waters further off shore, fishermen will adapt their fleet (i.e., larger vessels) and fishing seasons may change. Case in point, where the lobster season opens in the Gulf of St. Lawrence in early May, this may have to be moved back to March or April (new ice out times) when the fish stocks have not migrated too far off shore (pers. comm.).

In addition to anticipated changes in use in response to changes in fisheries and migration patterns, SCH is already observing an increase in the usage of select harbours, both in terms of the number of people and boats using the harbour facilities at any given time, as well as the number of days in the year the harbour is busy. This increase may be due in part to warming air temperatures and related changes in seasonality that prompt more human activity on the water and /or influence the distance and duration of travel. In fact, the DFO Climate Change Adaptation Client-Needs Workshop (2011) listed overcrowding as an existing infrastructure challenge: "*Overcrowding at some harbours is becoming a hazard.*"

10.5.3.2 Level of Risk

The impact, that harbour infrastructure will need to be adapted to changes in use, is somewhat related to the previously discussed impact about coastal infrastructure. Where usage patterns are increasing or vessel types are changing, changes can impose additional wear and tear that could weaken the asset's resilience to weather events. However, this impact focuses not on the state of the asset, but the asset's ability to support the Department's strategic outcomes. For example, as boating season lengthens (induced somewhat by temperature change), demands for harbour services may change, and DFO will have to reassess issues of safe and secure waters. Also, as fishing patterns shift along with ecosystem responses to climate change, there may be a need to update or relocate harbour infrastructure in order to support economically prosperous Maritime Sectors and Fisheries.

The impact ranking is Very High for both timeframes. The impact to operations and services (i.e., ensuring harbour infrastructure supports strategic outcomes) will be challenged by changes in climate, as well as socio-economic changes. For example, some changes will be a natural evolution of technology (e.g., fishing techniques and equipment), some will result from changes in the ecosystem (e.g., changes in fish range and distribution) and intensifying weather events may prompt others. The expense of adapting to these impacts could be considered Extreme: so too could the consequences of not adapting harbour infrastructure. However, changes in fisheries will happen slowly (over decades). With leadership and proper management, aligned with the provision of up-to-date Trends and Projections, the Department should be able to address the impact.

The ranking of Moderate for probability for the decadal timeframe stems from the fact that changes in harbour usage are site specific, and it is simply not known at this time if there is any effort by SCH or Harbour Authorities to track and map changes in use. Further, at the time of writing, it is unknown if there is research linking changes in use to the direct influence of climate change. For similar reasons, the uncertainty ranking for this impact is Moderate. While there is no question that particular harbours are experiencing dramatic changes in use, there is not much evidence about overall use trends.

For the 50-year timeframe, the probability ranking is Likely, and the uncertainty ranking is Low. The increase in the probability ranking relates to the age of infrastructure in concert with projected trends and projections for climate change.

There is a high level of confidence in saying that harbour infrastructure is at risk, which in turn poses great risk to Department operations and services. For that reason, the uncertainty ranking for the 50-year time frame is Low.

10.5.4 Coastal Infrastructure—Increased Maintenance Due to Biological Activity

Table 10–10 Coastal infrastructure—Increased maintenance due to biological activity

Impact	Increased maintenance costs due to greater biological activity of undesirable aquatic plants and animals associated with increased air and surface water temperatures, and decreased salinity		
	Impact severity	Probability	Uncertainty
decadal	Medium	Moderate	Low
50-yr	Medium	Likely	Low

10.5.4.1 Rationale

The 2005 Fisheries and Oceans Climate Change Risk Assessment Report listed "improved conditions for invasive species" as a risk factor associated with "changes in water temperature, abundance, quality, composition, and circulation patterns (Interis 2005)." This risk factor is directly related to concerns about the transportation of invasive species in ballast water.

The idea that changes in physical oceanographic and atmospheric variables could stimulate or worsen the presence of undesirable species in such a way as to negatively affect infrastructure, was vetted with SCH Directorate personnel in the March 2012 interviews. Indeed, experts pinpointed greater biological activity of invertebrate borers and aquatic algae, leading to increased maintenance costs. Later in the year, the 2012 National Risk Profile listed "*decreased salinity causing an increase in encrusting plants (barnacles) and increased activity of wood-boring invertebrates*" as a potential climate change impact (Interis 2012).

10.5.4.2 Level of Risk

The impact ranking associated with this is Medium: consequences can be significant, but can be managed under normal circumstances by the Department. While it is less certain that this ranking is appropriate for the 50-year timeframe, there was not enough evidence to warrant a higher ranking.

The probability of increased biological activity of undesirable aquatic plants and animals is parallel to the probability of the climate drivers that define species' productivity. However, the probability in the context of this report considers the strain placed on the Department if biological nuisances to infrastructure increase. For this reason, the probability is ranked as Moderate for the decadal timeframe and Likely for the 50-year timeframe, acknowledging that climate and oceanography parameters will become more hospitable to undesirable aquatic plants and animals with time. Examples of damage caused by invasive species, encrusting plants or wood boring invertebrates are in no short supply.

The uncertainty behind the impact is Low. Trends for sea surface temperature warming and decreasing salinity are clear with high levels of scientific confidence. The reason that the uncertainty ranking was not very low is because of limited information about where and to what degree this impact is already being felt. This makes it hard to assess the spatial extent of the impact and project future vulnerability.

10.5.5 Coastal Infrastructure—Structural Damage to Harbour Infrastructure

Table 10–11 Coastal infrastructure—Structural damage to harbour infrastructure

Impact	Harbour infrastructure (SCH and RPSS assets) increasingly vulnerable to significant and costly structural damage from ice rafting and ice pile up due to sea ice changes		
	Impact severity	Probability	Uncertainty
decadal	Medium	Moderate	High
50-yr	Medium	Moderate	High

10.5.5.1 Rationale

Ice can be both a protector and assailant to fixed coastal infrastructure. Paul MacDonald, an Environmental and Safety Engineer with SCH explains, “Harbours in the Gulf Region (Bay St. Lawrence, NS to New Mills, NB) are iced over from approximately December to April each year, albeit this time frame is somewhat variable in recent years. This effect results from a combination of pack ice (aka Arctic ice or drift ice) and static ice (aka bay ice or fast ice). The harbours in the Maritimes Region are generally considered to be ice free, for the most part. Once the ice forms (usually static ice first) and remains shore fast, it serves to protect the shoreline (including infrastructure) from wave attack. When ice formation is sporadic with open water behind it, it can be susceptible to rafting under appropriate wind conditions. The effects can be quite dramatic during a storm and /or tidal surge where the ice can raft up several meters and result in significant damage to infrastructure. Thinning ice can also present hazards to infrastructure, particularly during the formation and break up periods. Thin ice pans that form initially, or during the late stages of the spring thaw, can move back and forth in open water and under certain wind conditions the dynamic force from the moving ice can cause significant damage to infrastructure, particularly timber structures (pers. comm.).”

The 2005 Fisheries and Oceans Climate Change Risk Assessment Report included ‘increased ice movement’ in a table listing impacts due to changes in ice cover. The 2012 National Update did not mention ice movement as a potential cause for infrastructure damage. Instead, it listed generalized impacts to infrastructure. There could be many climate-related causes of infrastructure damage, and experts interviewed during this impact, opportunity and vulnerability analysis corroborate the inclusion of ice rafting and ice pile-up as a concerning impact.

In 2011, the DFO Climate Change Adaptation Program Client-Needs Workshop identified the desire for additional studies and an ice modeling tool that could describe, track and estimate ice cover and movement for small craft harbours. The need for this tool was said, at that time, to be particularly strong for the Gulf St. Lawrence.

March 2012 interviews with experts reiterated the concern about ice damage to infrastructure and agreed that ice cover and modeling in relation to small craft and harbour operations is a significant knowledge gap.

10.5.5.2 Levels of Risk

Concerns about damage to infrastructure from ice rafting and pile up are warranted, particularly in the decadal period: especially in Labrador and Quebec, and less so in the southern half of the Atlantic Basin (Lambert et al. 2012). The Probability ranking for both timeframes is Moderate: defined in the IVO Summary Table as, 'has occurred here before, or has been observed in similar circumstances'. The Uncertainty ranking is High for both timeframes. The uncertainty about this impact stems from questions about how much ice will actually be left for SCH to have to deal with in the future, and to what degree will changes expected in streamflow characteristics have the potential to change the risk of ice jams in rivers?

While respecting the fact that ice-related damage to harbours can render infrastructure unusable or be extremely costly to repair, the impact ranking for both timeframes is Medium. From a Departmental perspective, events of serious damage from ice rafting or pile up can be dealt with under normal circumstances. A more severe impact ranking was considered, but Senior Project Engineer with SCH, Tony Mackey P. Eng., stated that in his experience "*sea ice does not have the impact that it had 30 to 40 years ago. In Newfoundland and Labrador, there has been minimal or no damage, as the result of ice, mainly due to the fact that it is not present around 80-90% of (their) facilities. If it is, it usually is not packed tight and does not stay present for long periods of time* (pers. comm.)." Mr. Mackey pointed out that his expert opinion relates to Newfoundland and Labrador specifically, so the same observation may not be true for other regions. While the Maritimes Region does not have significant issues of ice impacts, there have been issues in the Gulf of St. Lawrence.

10.5.6 Coastal infrastructure—Compromised by Rapid Coastal Erosion

Table 10–12 Coastal infrastructure—Compromised by rapid coastal erosion

Impact	Coastal infrastructure (SCH, CCG and RPSS assets) and access to coastal infrastructure compromised by rapid coastal erosion		
	Impact severity	Probability	Uncertainty
decadal	Very high	Almost certain	Low
50-yr	Very high	Almost certain	Low

10.5.6.1 Rationale

The CCG Aids to Navigation Technical Services Group is challenged by coastline erosion and siltation, especially along the north shore of Prince Edward Island and eastern shore of New Brunswick. Shoreline erosion is endangering fixed aids including but not limited to: towers, lighthouses, range lights, breakwaters and repeater stations. These assets are necessary to maintain safe and secure waterways. The inherent purpose of these assets requires that they be located near the shoreline, thus heightening vulnerability to coastal impacts. The concern is that rapid coastal erosion is impacting the provision of service and requiring assets to be repaired or relocated, engendering significant expense.

In addition to flooding and wave damage, access routes to infrastructure are subject to significant coastal erosion exacerbated by sea level rise and the evolving wave environment, intensifying rainfall events, periods of drought, and an increase in the number of times the coastal geology passes through the freeze-thaw cycle. In many locations, erosion of unconsolidated sediment, gypsum, limestone and shale is undermining roadbeds and facility footings as coastlines change in concert with sea level rise (McCulloch et al., 2002).

In the 2012 National Climate Change Risk Profile, coastal erosion and retreat is listed as an impact associated with multiple climate risk factors/drivers: changes in precipitation, changes in wind patterns, storms, sea level rise, and changes in ice cover and sea ice (Interis 2012). It also came up during the March 2012 interviews with experts in SCH.

10.5.6.2 Levels of Risk

It is reasonable to expect that the Department can address erosion-infrastructure issues under proper management for both time scales. That being said, not addressing the vulnerability of coastal assets to erosion could result in disastrous marine accidents (i.e.,, emergency response infrastructure is affected) and significant costs to replace or relocate needed infrastructure. For this reason, the impact ranking is Very High for both timeframes. The Department's capacity to deal with the impact will largely be a question of both budget and departmental leadership in efforts to assess site vulnerabilities and infrastructure priorities.

There is an Almost Certain probability that current locations of significant erosion will continue to be problematic, with erosion becoming more rapid especially in the Maritimes and Gulf of St. Lawrence. It is also likely that new areas of erosion will emerge as coastal features become less stable due to heightened exposure to storm surge and wave energy as a result of an increasing mean sea level and intensifying storm activity (reductions in return period of storms). Issues stem from erosion undercutting, stranding, or compromising the safety and or functionality of infrastructure, including fixed aids.

The level of uncertainty about this impact is Low, because the affects of coastal erosion are obvious, with no shortage of examples of damage that is occurring and can occur. The ranking is not very low due to uncertainty degree to which SCH currently has to allocate resources to address erosion problems. In other words, the impact rating may be debatable: SCH may suggest a higher ranking, particularly for the 50-year timeframe.

10.5.7 Coastal Infrastructure—Floating and Fixed Navigational Aids

Table 10–13 Coastal infrastructure—Floating and fixed navigational aids

Impact	Increased need to repair, relocate or replace floating and fixed navigational aids due to winds and storms		
	Impact severity	Probability	Uncertainty
decadal	Medium	Moderate	High
50-yr	Medium	Moderate	High

10.5.7.1 Rationale

The 2005 Climate Change Risk Assessment Report stated that DFO personnel were concerned that "modernization initiatives (e.g., decreased buoy maintenance) may increase the susceptibility of certain aids to damage (Interis 2005)." While the ultimate risk is one of personal injury or loss of life related to navigation, the risk to operations and services is largely financial—although Coast Guard Mariners are not immune from risks of marine incidents if channels are not properly marked.

The issue of winds, waves and storms forcing floating and fixed aids out of position came up again in the DFO's internal 2009 Climate Change Questionnaire. The issue remained significant enough to be reiterated as a major climate change impact in the CCG Maritimes Region Environmental Scan (2011): "*Likely impacts of climate change on CCG programs and services include increases in Aids to Navigations services as floating aids are knocked off position.*" Later the same year at the Maritimes Initial Regional Meeting of ACCASP, CCG personnel stated that an observed impact to operations and services that is expected to worsen with intensifying storms is the strain on resources to ensure floating aids systems are accurate. Not doing so could result in accidents if system users are unaware that floating aids are off position. Further evidence of the seriousness of this impact is that it was mentioned again at the Climate Change Forum of the CCG Maritimes. Specifically listed as one of five challenges faced by the CCG was, "*more floating aids will have to be re-positioned and fixed aids may require more repairs* (2012)." For example, Yves Jacques, a Marine Aids Review Officer with the CCG, stated that, "*waves crashing on breakwaters (intensified by sea level rise) have mined the base of range light towers located on breakwaters* (pers. comm.)."

10.5.7.2 Level of Risk

Under normal circumstances, the Department can manage the financial impact of repairing, replacing and relocating floating aids, though resources are strained to do so. As marine traffic increases in the northern portion of the Atlantic Basin (due to disappearing sea ice and warming temperatures), and there is a possible increase in the number of fall storms in the northern portion of the mid-latitudes, the strain on the budget for aids to navigation could be further challenged. For these reasons, the impact ranking is Medium for both timeframes (i.e., significant event, but can be managed under normal circumstances).

Winds and storms are already causing the need to repair, relocate or replace floating aids in Atlantic Canada, according to the CCG Technical Services Group. For this reason, the probability ranking is Moderate. The reason the ranking is below Likely stems from the fact that it is difficult to directly associate the movement of aids with weather conditions that have been exacerbated by climate change.

From the climate change point of view there is scientific uncertainty about means and extremes for storm tracks and intensities. Therefore, the uncertainty ranking is High for both timeframes. The impact to the Department posed by the requirement to repair, relocate or replace floating aids is directly linked to the extent to which changing trends in winds, waves and storms impact the aids.

10.5.8 Coastal Infrastructure—Vessel Operational Requirements and Modifications

Table 10–14 Coastal infrastructure—Vessel operational requirements and modifications

Impact	Increased costs associated with increased vessel operational requirements and modifications to meet changing needs of the marine environment due to changing sea ice, storms and winds, and waves		
	Impact severity	Probability	Uncertainty
decadal	Very high	Almost certain	Moderate
50-yr	Very high	Almost certain	Moderate

10.5.8.1 Rationale

When CCG was asked in the March 2012 interviews what is needed from Science counterparts in regards to knowledge of climate change, the answers could be summarized as a desire to know, to the extent possible, what their marine operating environment will be. This understanding is critical not only for the current and future provision of services, but also to ensure that new vessels are designed with the evolving marine environment in mind. In the words of Gary Walsh, CCG-Fleet, "New designs may have to be considered to ensure that vessels are capable of working in an evolving marine environment for the next 20-30 years (minimum) (pers. comm.)." Mr. Walsh also pointed out at the 2011 Maritimes Initial Regional Meeting of ACCASP that, "The Coast Guard will need to have a clear understanding of the extent to which the marine environment will change because it could impact on the final design chosen to replace the assets currently in service. If the marine environment becomes more extreme, this could impact on the operating distance, speed and endurance of traditional designs (DFO 2011)."

The 2005 Climate Change Risk Assessment Report listed the pursuit of fleet recapitalization as a planning priority to address the risk of increased demand to provide emergency response (risk 4). The same report also listed "*increased costs of maintaining DFO fleet*" as a potential impact associated with risk 4 (Interis 2005). Fleet maintenance and renewal was reiterated as a risk in the 2012 National Climate Change Risk Profile: listed as, "*increased costs associated with vessel design and modification to meet changing needs and higher operational requirements* (Interis 2012)."

Compounding the issue of the questionable adequacy of the CCG fleet for the evolving climate is an observed increase in demand for CCG services. An increased resource demand was first listed in the 2005 Climate Risk Assessment Report. Later, one of the questions in the 2009 internal CCG Climate Change Questionnaire was, 'how do you expect climate change to impact your sector in the future?' The synthesized response sheet reported an increased demand on services (e.g., increasing ice escorts, ice breaking requests, search and rescue incidents, response to marine environmental spills, etc.), thus requiring more fleet *or* sacrificing levels of service to both mariners and demands for Science Assistance. As stated in the minutes of the 2011 Maritimes Initial Regional Meeting of ACCASP, "*Global warming and its potential impacts will require an increase in scientific effort to better grasp the extent and impacts related to the phenomena. Some of the data necessary to understand the problem will require at-sea collection. Based on the science required, the methods and equipment to be used, and the areas of operation, Science will have to discuss and engage CCG so that proper at-sea platform can be readied to carry out the work required.*"

The 2012 National Climate Change Risk Profile addressed the impact of strain on fleet resources when listing the potential impact of "*reduced support for research activities, due to re-deployment of vessels to emergency response activities* (Interis 2012)."

An overall increase in program demand for services and fleet was reiterated at the CCG's Climate Change Forum in 2012. However, the notable comment was made that in addition to discussing fleet upgrades and renewals to accommodate an increase in demand for services and fleet, CCG should also be investigating and exploiting different methods or technologies to meet changing service and operational requirements.

The expected reduction in sea ice is likely to be one of the most important environmental factors impacting fleet operations in the Atlantic LAB. Areas that are currently ice-covered during winter are likely to either have less sea ice or no ice at all in the coming decades. This will have a direct impact on changes to the wave climate for these areas that, in turn, would impact fleet demands.

10.5.8.2 Level of Risk

In the context of this risk assessment, the question underpinning this impact relates to whether the CCG fleet will be able to continue services including, but not limited to: ice breaking, escorts, supporting scientific research, environmental response, and search and rescue.

The impact ranking is Very High for both timeframes. This ranking stems from not only the economic cost of fleet renewal and modification, but also the critical importance of approaching fleet renewal and updates with climate trends and projections in mind. Changes in potential use must also be considered (e.g., anticipated increased demand to respond to sovereignty issues and humanitarian efforts).

The probability that there will be costs incurred during vessel design and modification is Almost Certain. The notion being, there are obvious significant costs associated with the CCG vessel replacement project. Similarly, there is no question that present-day designs and modifications are accommodating climate trends and projections.

The uncertainty ranking of Moderate relates to the question of whether climate change will induce costs that are *additional* to costs that would have otherwise been incurred. As well, there is some uncertainty about the degree to which changes in the marine climate in conjunction with changes in demands for operations and services are helping to catalyze fleet modifications and replacement.

10.6. ACCESS AND NAVIGABILITY OF WATERWAYS

Climate change impacts to access and navigability of waterways encompasses:

- Ice Routing and Information Services
- Ice Breaking Services
- Canadian Hydrographic Services
- Dredging
- Maintaining Navigational Aids

The climate change impacts to access and navigability of waterways listed in the IVO Summary Table are highlighted in the table below.

Table 10–15 Impacts to access and navigability of waterways listed in IVO summary

Climate Change Impact	Time-frame	Impact Severity	Probability	Uncertainty
Need for increased ice routing and information services magnified due to changes in sea ice location and movement	decadal	Very high	Moderate	Moderate
	50-yr	Very high	Unlikely	Low
Increased demand for ice breaking services due to changing ice conditions	decadal	Very high	Almost certain	Moderate
	50-yr	Very high	Moderate	Low
Increasing need to create / update CHS charts for waters where sea ice historically, but no longer, impedes travel	decadal	Very high	Almost certain	Low
	50-yr	Very high	Almost certain	Moderate
Increased need to update CHS charts, and chart datum due to mean sea level rise and rapid coastal erosion	decadal	Medium	Almost certain	Moderate
	50-yr	Medium	Almost certain	Very low
Increased need for dredging due to sediment transport caused by changes in sea level and coastal erosion	decadal	Very high	Almost certain	Very low
	50-yr	Very high	Almost certain	Low
Increased need to relocate floating aids due to siltation of channels caused by rapid coastal erosion	decadal	Medium	Almost certain	Low
	50-yr	Medium	Almost certain	Low

10.6.1 Access and Navigability of Waterways—Ice Routing and Information Services

Table 10–16 Access and navigability of waterways—Ice routing and information services

Impact	Need for increased ice routing and information services magnified due to changes in sea ice location and movement		
	Impact severity	Probability	Uncertainty
decadal	Very high	Moderate	Moderate
50-yr	Very high	Unlikely	Low

10.6.1.1 Rationale

The CCG is experiencing an increased demand for their ice-related services and a change in how they operate. These changes are particularly evident in Newfoundland and Labrador. Changes in ice conditions are providing commercial clients with increased opportunities: they are able to travel in areas they were never able to before. For example, areas such as the Strait of Belle Isle have opened up for extended periods of time during the winter (Gary Walsh, pers. comm.). As well, commercial traffic, including Ferry Services, has extended not only the area in which they are traveling, but also the length of time they are staying in those areas. These shifts in marine activity affect ice routing and information services, as well as ice breaking services.

Both the 2005 Climate Change Risk Assessment Report and its 2012 National Update acknowledged an increased need for ice routing and information services as a potential climate change impact. The 2005 report states, "*In the Arctic, an earlier ice break-up and a later freeze-up could allow more dangerous multi-year ice to be distributed in shipping lanes. This would increase the requirement (both the quantity and coverage) of ice reconnaissance activity*" (Interis 2005)." This transient ice makes its way into the Newfoundland and Labrador area. As stated in the report,"*Unlike the complex relationship between various climate risk factors and a dynamic and multi-faceted ecosystem, the presence of dangerous multi-year sea ice in shipping channels has a clear and direct impact on Departmental resources. While uncertainty remains regarding the extent and timing of climate change effects, there is little uncertainty regarding how it could affect DFO* (Interis 2005)."

The 2012 National Climate Change Risk Profile Update listed the impact as, (a need for) "*additional navigational advice to assist mariners in coping with new challenges from floating and rafting sea ice* (Interis 2012)." This observation has been repeated in multiple CCG documents assessing climate impacts to operations and services over the last few years. For example, the 2009 internal

Climate Change Questionnaire highlighted an expectation that "*ice floe conditions will require more ice escorts.*"

10.6.1.2 Level of Risk

What impact would an increase for ice routing and information services have on Department operations and services? The obvious answer is that it would pose an additional strain on resources (e.g., budgets, personnel, vessels, equipment). A worst-case scenario would be that the inability to adequately maintain this service would result in an environmental incident or marine accident. Such situations could trigger the previously mentioned impact of potential increases in reputational and legal costs. The serious nature of the consequences of not providing sufficient ice routing and information services warrants the impact ranking of Very High in both timeframes.

There will be increasingly larger changes in sea ice concentration with time, resulting in a decreasing level of confidence that there will be an increased demand for ice routing and information services as time goes on (Loder and van der Baaren, 2013). For this reason, both the probability ranking and uncertainty ranking for this impact decrease between the decadal and 50-year timeframe: a moderate probability for the decadal timeframe, and an unlikely probability for the 50-year timeframe; a moderate uncertainty for the decadal timeframe decreased to a low uncertainty for the 50-year timeframe.

10.6.2 Access and Navigability of Waterways—Ice Breaking Services

Table 10–17 Access and navigability of waterways—Ice breaking services

Impact	Increased demand for ice breaking services due to changing ice conditions		
	Impact severity	**Probability**	**Uncertainty**
decadal	Very high	Almost certain	Moderate
50-yr	Very high	Moderate	Low

10.6.2.1 Rationale

The 2005 Climate Change Risk Assessment Report stated, "some impacts are being felt already, such as an increased demand for icebreaking and escort activities (Interis 2005)." The first-hand experience of the CCG seven years later confirms that strained resources due to additional demand for ice breaking services remains a growing issue.

At the 2011 Maritimes Initial Regional Meeting of ACCASP, currently observed challenges to CCG ice breaking services were explained, "*Several mild winters has led to an expanded scope of operations for the ice breaking fleet in the Gulf of St. Lawrence that is eroding ability to meet levels of service. Decreased ice season and less ice is leading to new shipping ventures that traditionally have* *not had to be serviced by Coast Guard. New winter ferry runs from Magdalene Islands to Quebec as well as a ferry running from Corner Brook up the coast of western Newfoundland have been approved as pilots during the last three winters. Coast Guard 'ice levels of service' dictate that ferries take priority. Since these are new services, they have to be addressed using ice breaking capacity that has not expanded. As a result, potential exists for erosion of level of service to traditional shipping clients and the ports that rely on their business. This could imperil icebreaking fees that Coast Guard receive from clients to respect levels of services* (DFO 2011)."

10.6.2.2 Level of Risk

While changes in climate and thus ice conditions are extending commercial activity, the CCG is directed to operate within 'traditional levels' of service and timeframes. Dan Frampton, Superintendent of Ice Operations, points out that traditional timelines need to change to reflect changing commercial use (pers. comm.). There is a sense this type of increased activity carries the risk of not being able to continue to meet the demand of commercial clients. Should this be the case, the Department will not achieve the strategic outcome of providing safe and secure waterways. As well, there is great risk to human life and property if DFO fails to provide sufficient ice breaking services. Lastly, even though the overall trend is for decreasing sea ice and changes in extent and duration of ice, natural variability within this trend means that it is very likely there will still be years with significant need for ice breaking services: certainly in the decadal timeframe, and also into the 50-year timeframe. For all these reasons, the impact is ranked as Very High for both timeframes.

In recent years, increased demand for ice breaking services in the Atlantic Basin have occurred regularly. Therefore the probability associated with this impact is Almost Certain for the decadal timeframe, but decreases to a ranking of moderate for the 50-year timeframe. This is because of an expected continued reduction in sea ice as a result of climate change. Similarly, uncertainty around this impact is Low for the 50-year timeframe, but increases for the decadal timeframe given the near-term changing nature of ice, compounded by changing patterns in marine traffic in those areas once impeded by ice.

10.6.3 Access and Navigability of Waterways—CHS Charts

Table 10–18 Access and navigability of waterways—CHS charts

Impact	Increasing need to create / update CHS charts for waters where sea ice historically, but no longer, impedes travel		
	Impact severity	Probability	Uncertainty
decadal	Very high	Almost certain	Low
50-yr	Very high	Almost certain	Moderate

10.6.3.1 Rationale

A CHS priority is to relate to increased marine traffic, of all kinds, now travelling in waters once impeded with ice. As stated in the 2005 Climate Change Risk Assessment Report, "The availability of accurate charts can reduce the likelihood of navigation incidents, particularly in the Arctic, but there is concern that the Canadian Hydrographic Service of the Science Sector will not have the capacity to respond to increased charting requirements that may arise as a result of climate change. While the Northwest Passage and areas of high economic activity are currently well-charted, accurate charts are not always available for more remote areas, as well as **some areas of Newfoundland and Labrador** and the Haida Gwaii. Arctic charts are sometimes based on data collected by ships of opportunity with little or no assurance of accuracy. Other data include widely spaced spot soundings taken through the ice that give only a minimal indication of the actual water depths, and can be misleading when used without an understanding of their reliability (Interis 2005)."

Interviews in 2012 with CHS personnel confirmed that given their current financial resources, only shipping corridors are surveyed. Outside of these corridors, commercial and private ships may provide CHS with soundings but, as mentioned above, there is little or no assurance of accuracy. Furthermore, when private companies are doing resource exploration in the Arctic, they often do not share soundings as these are considered proprietary. CHS will accept soundings provided by private companies to produce charts, but only with the understanding that such information will be made public.

The 2012 National Climate Change Risk Profile Update referenced the impact of needing to address increased charting requirements and costs for the Canadian Hydrographic Service, particularly in the Arctic. However, the requirement for charts extends well into the Atlantic Basin, particularly in the Labrador Sea.

As a means of addressing the risk inherent with increased traffic in uncharted, or unreliably charted waters, CHS Regions are collaborating to pool their limited financial resources to address national field survey priorities. These priorities are to be determined with a recently developed CHS tool that takes into consideration a suite of factors for a specific geographic area; for example, traffic, depth of water, dynamic bottom, complexity of entry channels, and search and rescue response time.

10.6.3.2 Level of Risk

What is the impact of increasing charting requirements to DFO operations and services? While the need for these charts is not debated, the Departmental impact of providing the charts would entail a large-scale, long-term investment. For this reason, the impact is ranked as Very High for both timeframes.

There is unquestionable benefit to mariner safety if CHS-produced charts for currently uncharted territory were to become available. Therefore the probability ranking is Almost Certain.

The reason the uncertainty ranking is Moderate for the 50-year timeframe and Low for the decadal, stems from questions about the availability of charts from private firms, or other governments (e.g., Russia). If the need for CHS to provide charts lessens in the future due to changes in sovereignty or market-based charting services, the impact ranking would lessen.

10.6.4 Access and Navigability of Waterways—CHS Charts and Chart Datum

Table 10–19 Access and navigability of waterways—CHS charts and chart datum

Impact	Increased need to update CHS charts and chart datum due to mean sea level rise and rapid coastal erosion		
	Impact severity	Probability	Uncertainty
decadal	Medium	Almost certain	Moderate
50-yr	Medium	Almost certain	Very low

10.6.4.1 Rationale

As mentioned in the 2005 Climate Change Risk Assessment Report, inaccurate (or absent) charts are of particular concern off the coast of Labrador because of heightened risk of emergency response incidents “ranging from vessel accidents and search and rescue operations, to the disposal of contaminated bilge water (Interis 2005).”

The fact that mean sea level rise in the Atlantic Basin is projected to be higher than global estimates creates the regional need to update chart datum, which is critical to marine navigation and mariner safety as well as the prevention of environmental incidents. SCH has also expressed concern about needed adjustments to wharves and slipways due to mean sea level rise.

Rapid shoreline erosion resulting from physical climate drivers (e.g., sea level rise and changes in tide levels, increased exposure to waves, heightened storm surge) is causing sedimentation of navigational channels in coastal areas. In turn, increasingly challenging sedimentation issues are necessitating additional surveillance and new surveys and charts.

Concerns about this impact were expressed by DFO personnel in the 2012 interviews and in follow-up correspondence. It also came up in the National Climate Change Risk Profile Update. The Update listed potential impacts such as: damage to vessels due to incidents related to navigation, increased charting requirements and associated costs, and environmental pollution related to leaking contaminants from vessels due to navigation incidents.

10.6.4.2 Level of Risk within the Gulf of St. Lawrence

The need to update charts and chart datum because of changes in physical oceanographic variables will require resources that CHS currently does not have. The capacity to update charts and chart datum is further compromised by the priority need to create charts for northern waters (i.e., currently uncharted).

For both the decadal and the 50-year timeframe, the impact of this need to the Department is Medium in the Gulf of St. Lawrence. As stated by Phil MacAuley with CHS, "The impacts (of relative sea level rise) and sensitivity are much greater in the Gulf (of St. Lawrence) because there, vessels navigate with very little below keel clearance. In most other locations the impacts to operations and services will be much lower as increasing sea levels will not drive chart updates as quickly as in the Gulf as it will have less impact on the safety of navigation (pers. comm.)."

The probability ranking is Almost Certain for both time frames due to 'almost certain' projections about continued sea level rise and already observed daily battles with coastal erosion and sedimentation in certain parts of the Atlantic Basin. As well, the impact is Almost Certain because there is no disputing the budget restraints of CHS and competing needs for its attention (i.e.,, focus on northern waters). The uncertainty for this impact is Moderate for the decadal timeframe, but Very Low for the 50-year timeframe. The reason for the decrease in uncertainty over time is because trends for changes in sea level, ice melt, precipitation and runoff as it affects lake and river levels, and climate drivers affecting erosion cumulatively cause charts to be increasingly *inaccurate* over time. Thus, while impacts are not occurring rapidly (hence the moderate uncertainty for the decadal timeframe), the need to update charts and chart datum becomes increasing critical in parallel with continued changes in climate.

10.6.4.3 Level of Risk outside of the Gulf of St. Lawrence

The impact ratings associated with the increased need to update CHS charts and chart datum due to mean sea level rise and rapid coastal erosion represent the circumstance within the Gulf of St. Lawrence only. For regions other than Gulf of St. Lawrence, the rankings would be quite different. There is less urgency to update charts and chart datum due to mean sea level rise and rapid coastal erosion. Therefore, outside of the Gulf of St. Lawrence, the impact to the Department would be Low, but probability Almost Certain for both timeframes.

The level of uncertainty in this statement is Moderate for the decadal timeframe, but Low for the 50-year timeframe. The reason uncertainty lessens with time reflects the cumulative impacts of sea level rise and coastal erosion with time.

It should be noted that erosion patterns and issues are changing throughout the LAB as sea level and wave energy rise to meet sedimentary rock layers. Therefore, **it is quite possible that the impact severity levels of coastal erosion in areas outside of the Gulf of St. Lawrence could become MODERATE to HIGH toward the end of the decadal timeframe** (e.g., Maritimes) in concert with rising sea level.

10.6.5 Access and Navigability of Waterways—Dredging

Table 10–20 Access and navigability of waterways—Dredging

Impact	Increased need for dredging due to sediment transport caused by changes in sea level and coastal erosion		
	Impact severity	Probability	Uncertainty
decadal	Very high	Almost certain	Very low
50-yr	Very high	Almost certain	Low

10.6.5.1 Rationale

Sedimentation is a climate-induced issue with repercussions to CCG and SCH operations. This impact was listed at the DFO Climate Change Adaptation Program Client-Needs Workshop (SCH 2011), and "changes in sediment patterns" was highlighted as a key information gap. Both the 2005 Climate Change Risk Assessment Report and the preceding 2012 National Update listed climate change-induced sedimentation transport as an issue to the access and navigability of waterways, with particular concern in areas of the Gulf of St. Lawrence, coastal Quebec, the north shore of PEI, the Magdalen Islands, and the New Brunswick coast (Interis 2005 and 2012). When interviewed in March 2012, DFO personnel suggested that sediment transport research should be focused where the need for dredging is already high and is noticeably intensifying.

10.6.5.2 Level of Risk

CCG personnel also stated that it is their understanding that DFO is not prepared to expand dredging activities (currently limited to the St. Clair River, the St. Lawrence, and select small craft harbours). It is also acknowledged that every time dredging occurs there is the potential for the mobilization of contaminants. However, given the serious consequences of rapid sedimentation to navigable waterways in the areas of core fishing harbours, there is hope that ACCASP will create tools to model sedimentation in priority areas of concern, and simultaneously experiment with mitigation measures. Another option that may have to be explored if dredging is not expanded in problematic areas is the relocation of the harbour, but this option is far more complicated with greater reputational and financial risk. For this reason the impact ranking for an increased need for dredging is Very High.

An Almost Certain ranking is assigned because channel sedimentation issues and calls for additional dredging are already being observed. The uncertainty for this ranking with this impact is Very Low for the decadal timeframe but increases to Low for the 50-year timeframe.

10.6.6 Access and Navigability of Waterways—Floating and Fixed Aids

Table 10–21 Access and navigability of waterways—Floating and fixed aids

Impact	Increased need to relocate floating and fixed aids due to coastal erosion and siltation		
	Impact severity	Probability	Uncertainty
decadal	Medium	Almost certain	Low
50-yr	Medium	Almost certain	Low

10.6.6.1 Rationale

The CCG Maritimes Region Environmental Scan (March 2011) linked impacts to CCG programs and services in five ways, one of them being: increases in Aids to Navigation services as floating aids are knocked off position.

During the March 2012 interviews, Claire MacLaren, CCG Supervisor, Operations, Aids to Navigation, stated that the biggest problem the Technical Services Group encounters is soil erosion: the sheer amount of shore front property lost annually (pers. comm.). This, of course, puts fixed aids (lighthouses/light structures) in danger. As well, it continuously requires relocation of floating aids due to the siltation of the channel. This issue is most notable on the north shore of PEI, Eastern shore of New Brunswick and Madeleine Islands. The problem requires surveys to be completed to provide water depths and contours that enable recommendations for new positions for the floating aids to best mark the channel. The increased demand on the CCG to conduct such surveys is also a climate change impact to operations and services.

Ms. MacLaren said, “Return periods for siltation would certainly be useful (pers. comm).” The 2005 Interis report stated that a proposal was being prepared “as part of the National Disaster Mitigation Strategy for Public Safety and Emergency Preparedness Canada, to seek funding to assess storm surge risk areas relative to the location of harbours (Interis 2005).” The proposed work was to “address a preventative response measure, and includes the conduct of a cost-benefit analysis regarding the storm-proofing and/or the re-location of the Department’s infrastructure (Interis 2005).” It is not known if, or to what extent this work was completed, but it is suspected it was not completed in that information of such a study never came up during interviews. Instead, DFO personnel from sectors outside Science were asking for this kind of study to be done.

Yves Jacques, a Marine Aids Review Officer with the CCG, points out that fixed aids are not only at risk of damage from coastal erosion, but are also at risk of becoming compromised as accurate navigational aids. For example, the Cap aux Meules range lights (Iles de la Madeleine) are no longer indicating the safest channel due to some accumulated sedimentation. There is now a need to move one of the towers in order to better reflect the safest channel (pers. comm.). Another example regarding the coastal erosion is the Pointe de L'est tower has fallen on the ground after a land collapse (pers. comm.).

This impact was also mentioned in the 2009 CCG Climate Change Questionnaire, the 2011 Maritimes Region Environmental Scan, the 2005 Climate Change Risk Assessment Report, the 2011 Maritimes Initial Regional Meeting about ACCASP, and the 2012 CCG Maritimes Region Climate Change Forum.

10.6.6.2 Level of Risk

The impact is ranked Medium for both timeframes. The climate change exacerbated need to address sedimentation of navigable channels is critical because inaccurately marked channels create potential for disaster (e.g., marine accidents, environmental incidents). But this is not the central question. The question underlying the impact ranking is, what are the impacts to the Department if they do or do not keep channels marked accurately. From this perspective, the impacts are of Medium ranking because the resources required to survey and relocate floating aids is significant, but can be managed under normal circumstances. However, the Department must keep in mind that demands are increasing for vessel support (e.g., increased emergency response, relocation of aids due to winds, waves and storms), making it increasingly difficult to adequately accommodate all needs and levels of service. This begets the question of a large-scale, long-term strategic commitment of resources to better match future fleet and equipment to Departmental demands for service. Not doing so will compromise all Strategic Outcomes.

The Almost Certain ranking reflects the expert opinion of the CCG Technical Services Group, Aids to Navigation. Sedimentation of channels and the battle to avoid marine incidents from inaccurately marked channels is a present-day issue. The uncertainty about this impact is Low on both timeframes.

10.7 POTENTIAL OPPORTUNITIES PRESENTED BY CLIMATE CHANGE

Intermittent or progressive changes in climate alter the circumstances in which DFO operates and provides service. The IVO Summary Table focused on impacts that are, or could potentially negatively strain programs and services. However, not all operational changes may be negative: some may be neutral and some may be positive. Knowledge and information about projected future changes in the marine environment related to climate change presents an opportunity for sectors within DFO to incorporate adaptation strategies into their business plans. Changes in climate are expected to occur gradually over the next century and this will allow sectors such as CCG, SCH, RPSS and CHS to develop long-term plans to accommodate for this.

An example of a neutral or positive change to operations and services could be the decreasing need for ice breaking services in the Gulf of St. Lawrence and Newfoundland and Labrador. The change could be considered neutral in that the ice breaking ships would likely be deployed elsewhere, thus operating costs are not avoided. However, the redeployment would be positive in that other needed services would be accommodated (e.g., Scientific support).

As pointed out by DFO Research Scientist, Nancy Shackell, "warmer temperatures could mean higher survival, faster growth rates and higher productivity (longer growing season) for species where there is projected warming in their ecophsyiological range (pers. comm.)." Depending on which species prosper, and in conjunction with trends and projections for less sea ice and warmer air temperatures, there could be opportunities to create new harbours in the Atlantic Basin which would contribute to the strategic outcome of Economically Prosperous Maritime Sectors and Fisheries. However, ocean acidification (particularly in the 50-year timeframe) and hypoxia may temper this opportunity.

The Department is approaching a significant opportunity to build trust with clients and bolster its reputation as an internationally respected scientific agency engaged in climate trends and projections. Effectively communicating recent findings between Sectors (to enhance Sector strategic planning), with other government departments, clients (e.g., mariners, coastal communities, fishing and aquaculture industries), educators and the media, will serve to both inform (i.e.,, lessen risk) and build client trust. Bill Goulding, Regional Director of the Small Craft Harbours Directorate in Newfoundland and Labrador, stated in the March 2012 interviews that SCH has not been involved or consulted in any regional, municipal or community level planning to address climate or infrastructure issues and concerns (pers. comm.). In his expert opinion, there is an opportunity to share climate change information with the general public, Harbour Authorities and partners. Doing so could help to facilitate consideration of climate change into policies, procedures and operational strategies of all parties involved in ocean stewardship and mariner safety.

10.8 GAPS

There is a high degree of uncertainty inherent with climate projections for the Atlantic LAB. Of particular interest is reducing uncertainty about projections for storms, storm return periods, waves and winds in the Northwest Atlantic. Also of interest are component contributions to global and regional sea level rise: for example, the role of ice melt and changes stemming for ocean circulation patterns. Storms, winds, and waves in association with sea levels rising higher than global estimates, underpin hazardous storm surges throughout the Atlantic LAB. Of related interest is shifting resonant periods and tide heights in the Bay of Fundy.

A shift in the range and distribution of fish stocks is an impact that is of Departmental interest from an ecosystem, and non-ecosystem perspective. Having clearly defined indicators tied to climate conditions or events that would trigger shifts in fishing patterns would inform the identification of areas of future increased use and related risk vulnerability, and correlated deployment of both resources and personnel. As well, it would assist with harbour infrastructure planning and development: coordinating upgrades with changing patterns of use and the marine environment in which they have to function.

Waters in the Northwest Atlantic are largely uncharted, or charted within only widely spaced spot soundings taken through the ice that give only a minimal indication of the actual water depths and can be misleading when used without an understanding of their reliability. In many areas where charts do exist the chart datum is inaccurate.

Multiple climate drivers are working in concert with localized geology to dictate rates and events of coastal erosion. The need to better understand sedimentation rates and patterns is especially high for areas where the need for dredging is already intense and/or floating aids are consistently rendered inaccurate.

Summary of Science Gaps (i.e., areas needing reduced uncertainty) for the Atlantic LAB:

- Storm tracks, winds, and waves
- Return periods of storms
- Component contributions to global and regional sea level rise
- Ocean circulation patterns
- Tidal changes in the Bay of Fundy
- Range and distribution of fish stocks
- The ability to conduct soundings through ice and/or remotely
- Accurate chart datum
- Sediment transportation

10.9 EXPERT OPINION

The following Table (Table 10–22) lists interviewees involved in the March 2012, DFO Science interviews of DFO personnel regarding their risks to climate change hazards and impacts, capacity to respond, and desire for DFO Science to increase their understanding of climate change impacts in specific ways so their Sector can plan and respond accordingly. These interviewees were taken into consideration when developing the list of non-ecosystem impacts for the IVO Summary Table.

Table 10–22 March 2012 DFO interviewees about climate change impacts to operations and services

Small Craft and Harbour Directorate	
Paul MacDonald, Environmental and Safety Engineer	Maritimes and Gulf
Stéphane Dumont, Regional Engineer	Quebec
Bill Goulding, Regional Director	Newfoundland and Labrador
Real Property Safety and Security	
Kathryn Cooper-MacDonald RPSS Environmental Officer	Maritimes
Perry Rideout, RPSS, A / Director, Integrated Business Management	Maritimes
Brian Elson, RPSS A/Emergency Services Advisor	Maritimes
Rodolphe Lapierre, Chief, Assets and Project Management	Quebec
Susan LeBlanc Robichaud	Gulf Region
Craig Hogan, Acting Director	Newfoundland and Labrador
Canadian Coast Guard	
Gary Walsh, Superintendent of Operations	Maritimes
Randy Brown, Planning Officer	Maritimes
Dan Frampton, Superintendent, Ice Operations	Newfoundland and Labrador
Sandra Inglis, Superintendent, Aids to Navigation	Maritimes
Paul Rudden with the JRCC	Maritimes
Harvey Vardy, Acting Superintendent Search and Rescue from the JRCC	Maritimes
Claire MacLaren, Supervisor, Operations, Aids to Navigation	Maritimes
Dr. Bernard Doyon, Hydraulic Engineering Marine and Civil Infrastructures Integrated Technical Services	Quebec
Canadian Hydrographic Service	
Michel Goguen, Director Hydrography	Maritimes
Joe Manning, Manager	Newfoundland and Labrador

Key Internal DFO Documents Used in the Synthesis of Non-ecosystem Impacts
Climate Change Forum of the CCG Maritimes, 2012
Interis 2012, National Climate Change Risk Profile Update
Canadian Coast Guard Maritimes Region Environmental Scan, 2011
DFO, Initial ACCASP Regional Meeting in the Maritimes Region, December 9, 2011
AMEC, Small Craft Harbours Climate Change Study, 2011

Small Craft and Harbours Directorate Client-Needs Workshop, 2011
Canadian Coast Guard Climate Change Questionnaire, 2009
Interis 2005, Climate Change Risk Assessment for Fisheries and Oceans Canada

The following Table (Table 10–23) lists those technical experts specializing in DFO Infrastructure who were contacted to provide feedback on listed impacts and their rankings of severity and probability.

Table 10–23 Technical experts specializing in DFO infrastructure

Small Craft and Harbours Directorate	
Tony Mackey, Senior Project Engineer	Newfoundland and Labrador
Paul MacDonald, Environmental and Safety Engineer	Maritimes and Gulf
Real Property Safety and Security	
Robert MacDonald, Regional Director	Maritimes
Taryn Baker	Newfoundland and Labrador
Susan Leblanc Robichaud	Gulf
Yves Lavergne, Directeur, Services immobiliers et conformité environnementale	Quebec
Canadian Coast Guard	
Paul Bowering, A/Supt. Aids to Navigation	Newfoundland and Labrador
Sandra Inglis, Superintendent, Aids to Navigation	Maritimes
Paul Joyce, Superintendent of Waterway Development	Maritimes
Pierre Rouleau, Directeur intérimaire	Quebec
Yves Jacques, Marine Aids Review Officer	Quebec
Steven Neatt, Icebreaking, Escort and Flood Control	Quebec
Canadian Hydrographic Services	
Phillip MacAulay, Physical Scientist, Tides, Currents and Water Levels	Atlantic
Steve Parsons, Engineering Project Supervisor	Atlantic
Kent Malone, Senior Technical Policy Advisor	Atlantic
André Godin, Marées, courants et niveaux d'eau	Quebec
Denis Lefaivre, Gestionnaire, modélisation océanographique	Quebec
Roger Côté, Acquisition de données en lien avec les infrastructures	Quebec
Richard Sanfaçon, Gestionnaire, division des données hydrographiques	Quebec

10.10 CONCLUSION

Sector interviews reveal that personnel 'on the ground' or out to sea, see evidence of increased vulnerability to natural hazards exacerbated by climate change in their day-to-day operations. In fact, personnel from all Sectors have stated that they know they need to adapt operations and services, but feel they have lacked the 'hard' evidence to support their knowledge. Specifically, the CCG would like the ACCASP process to result in more information about the anticipated marine environment in which they have to operate and provide service. The CCG, SCH and RPSS sectors *all* stated that recent research about the type, extent and timing of anticipated changes in climate is welcomed for business planning and resource allocation purposes.

The framework of this report was to first synthesize a list of non-ecosystem climate change impacts that have been derived by expert opinion (obtained through interviews, internal documents and reports) and substantiated by the climate change trends and projections provided by DFO Science. Secondly, each impact was evaluated for the degree to which it would impede the achievement of Strategic Outcomes.

The outcome of this high-level Risk exposure analysis was a recognition that priority areas for adaptation options for the decadal timeframe include:

1. ensuring coastal infrastructure adequately supports the Department's strategic outcomes,
2. charting currently uncharted territory,
3. updating charts to reflect changes to coastlines, and
4. addressing sedimentation issues in navigable waterways.
5. Priority areas for adaptation options for the 50-year timeframe are the same as for the decadal timeframe, with one addition:
6. adapting harbour infrastructure for changes in use.

The climate drivers *most often* linked to non-ecosystem impacts listed in the IVO Summary Table were: winds, waves, storms, sea level rise and changes in sea ice.

When assessing the climate drivers associated with *only* the five priority action areas listed above, the most concerning climate drivers are: sea level rise, coastal erosion, and changes in sea ice.

There are multiple ways that climate change impacts to non-ecosystem operations and services can hinder the achievement of strategic outcomes. One way is to simply incur tremendous economic costs: such as, fleet renewal and modifications, introduction or relocation of harbour infrastructure to align with changing usage patterns, maintaining navigable waterways via increased dredging and navigational aids, repairing or deconstructing damaged wharves, charting waters in the north Atlantic, and being subject to an increasing amount of lawsuits. From another perspective, climate change impacts could impede economic prosperity if not addressed with proper management. For example, not providing adequate infrastructure to support fisheries would have a large impact on rural economies. Likewise, not maintaining navigable waterways with accurately placed floating navigational aids could bring harm to the boats and equipment requisite to fishing livelihoods.

There are also reputational and social consequences to consider if impacts are not addressed. The worst-case scenarios involve emergency services. For example, if the capacity to prepare for and respond to environmental incidents and search and rescue calls does not evolve in concert with climate change impacts (e.g., increased demand for service), there could be huge reputational costs as well as personal injury and loss of life. Similarly, if CHS is not provided the means and personnel to update or create charts for priority areas of concern, there is increasing risk of emergency services being needed over time.

Detailed climate impact research (e.g., area-specific sedimentation modeling, coastal sensitivity indexes capable of running multiple weather-event and/or climate scenarios) and adaptation tools for the Sectors' use in planning and development (e.g., harbour vulnerability assessment processes, engineering studies, tests of alternative infrastructure such as floating breakwaters) will do a great service in avoiding or mitigating the economic, environmental, social and reputational costs of climate change. As well, improved communication tools and processes for disseminating recent climate research, carried out both within and outside DFO Science, to the DFO Sectors (i.e., CCG, SCH, RPSS, CHS) will bolster their efforts in figuring out what it is they need to know and do, and why in the context of climate change. From this knowledge, the Sectors can act to implement climate change adaptation strategies into their business plans. The result will be greater Departmental resilience and successes with strategic outcomes.

10.11 REFERENCES

Batterson, M., Liverman, D. 2010. Past and Future Sea-Level Change in Newfoundland And Labrador: Guidelines for Policy and Planning. Newfoundland and Labrador Department of Natural Resources.

Canadian Coast Guard. Maritimes Region Environmental Scan. 2011. Internal Document.

Chassé, J., Perrie, W., Long, Z., Brickman, D., Guo, L., Lambert, N. 2013. Regional atmosphere-ocean-ice climate downscaling results for the Gulf of St. Lawrence using the DFO Regional Climate Downscaling System. Can. Tech. Rep. Hydrogr. Ocean Sci. (under revision)

Forbes, D. L., Manson, G. K., Charles, J., Thompson, K. R., Taylor, R. B., 2009. Halifax harbour extreme water levels in the context of climate change: Scenarios for a 100-year planning horizon. Geological Survey of Canada Open File 6346, iv+ 22p.

Galbraith, P.S., Larouche, P. 2013. Trends and variability in eastern Canada sea-surface temperatures. Ch.1 In: Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x +190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf.

Guo, L., Perrie, W., Long, Z. 2012: Possible North Atlantic extratropical cyclone activity in a warmer climate. Canadian Meteorological and Oceanographic Society Congress –CMOS. Victoria BC 5-9 June.

Guo, L., Perrie, W., Long, Z. 2013. The Impacts of climate change on the autumn North Atlantic wave climate. (submitted to JGR).

Han, G., Colbourne, E., Pepin, P., Tang, R. 2012. Statistical Projections of Physical Oceanographic Variables Over the Newfoundland and Labrador Shelf. Northwest Atlantic Fisheries Centre. Can. Tech. Rep. Hydrogr. Ocean. Sci. 6 pp.

Han, G., Ma, Z., Loder, J.W., Bao, H., van der Baaren, A. 2013. Mean sea level trends in the Northwest Atlantic: Historical estimates and future projections. Ch. 9 (p. 113-126) In: Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x +190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf.

Harvey, B.J., Shaffrey L.C., Woollings, T.J., Zappa, G., Hodges, K.I. 2012. How Large are Projected 21st Century Storm Track Changes? Geophysical Research Letters. Vol 39. 5 pp.

Interis Consulting Inc. 2005. Climate Change Risk Assessment for Fisheries and Oceans Canada.

Interis Consulting Inc. 2012. Department of Fisheries and Oceans National Climate Change Risk Profile: 2012 Update.

IPCC, 2007: Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, Martin L., Canziani, Osvaldo F., Palutikof, Jean P., van der Linden, Paul J., and Hanson, Clair E. (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 1000 pp.

Jiang, J., Perrie, W. 2006. The Impacts of Climate Change on Autumn North Atlantic Midlatitude Cyclones. *J. Climate*, 20: 1174–1187.

Jiang J., Perrie, W. 2008. Climate Change Effects on North Atlantic Cyclones. *J. Geophys. Res.*, 113, D09102, doi:10.1029/2007JD008749.

Kuhlbrodt, T., Gregory, J.M. 2012. Ocean Heat Uptake and its Consequences for the Magnitude of Sea Level Rise and Climate Change. Geophysical Research Letters. Vol 39. 6 pp.

Lambert, N., Chassé, J., Perrie, W., Long, Z., Guo, L., Morrison, J. 2013. Projection of future river runoffs in Eastern Atlantic Canada from Global and Regional climate models. Can. Tech. Rep. Hydrogr. Ocean Sci. 288: viii+34 p. http://www.dfo-mpo.gc.ca/Library/349262.pdf

Loder, J.W., van der Baaren, A. 2013. Climate change projections for the Northwest Atlantic from six CMIP5 Earth System Models. Can. Tech. Rep. Hydrogr. Ocean Sci. 286: xiv + 112 p. http://www.dfo-mpo.gc.ca/library/349550.pdf

Loder, J.W., J. Chassé, P. Galbraith, G. Han, D. Lavoie and others. 2013. Summary of climate change trends and projections for the Atlantic Large Aquatic Basin off Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3051 (under revision)

Long, Z., Perrie, W., Gyakum, J., Laprise, R., Caya, D. 2009. Scenario changes in the climatology of winter midlatitude cyclone activity over eastern North America and the Northwest Atlantic. *J. Geophys. Res.*, 114, D12111, doi:10.1029/2008JD010869.

Mandrak N.E., Cudmore B., Chapman P.M. 2011. National Detailed-Level Risk Assessment Guidelines: Assessing the Biological Risk of Aquatic Invasive Species in Canada. Can. Tech. Rep. Hydrogr. Ocean. Sci. 23 pp.

Mastrandrea, M., Field, C., Stocker, T., Edenhofer, O., Ebi, K., Frame, D., Held, H., Kriegler, E., Mach, K., Matschoss, P., Plattner, G., Yohe, G., and Zwiers, F. 2010. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. IPCC Cross-Working Group Meeting on Consistent Treatment of Uncertainties. Jasper Ridge, CA, USA.

McCulloch, M.M., Forbes, D.L., Shaw R.W. and the CCAF A041 Scientific Team. 2002. Coastal impacts of climate change and sea level rise on Prince Edward Island. Forbes, D.L. and R.W. Shaw Eds. Geological Survey of Canada, Open file 4261 xxxiv + 62 pp.

Perrie, W., Guo. L., Long, Z. 2013. Wave Climate Trends and Projections – GCM and RCM Results. Can. Tech. Rep. Hydrogr. Ocean. Sci. 9 pp (in prep).

Peterson, I.K., Pettipas, R. 2013. Trends in air temperature and sea ice in the Atlantic Large Aquatic Basin and adjoining areas. Can. Tech. Rep. Hydrogr. Ocean Sci. 290: v + 59 p. http://www.dfo-mpo.gc.ca/Library/350061.pdf

Strand R., Oughton, D. 2009. Risk and Uncertainty as a Research Ethics Challenge. National Committee for Research Ethics in Science and Techngology. Publication no. 9. 42pp

Williams, R., Daigle, R. 2011. Scenarios and Guidance for Adaptation to Climate Change and Sea-Level Rise – NS and PEI Municipalities. ACAS report prepared for the Climate Change Directorate, NS Environment. http://atlanticadaptation.ca/ns_projects

Xu F., Perrie, W. 2012. Extreme Waves and Wave Run-up in Halifax Harbour under Climate Change Scenarios, Atmosphere-Ocean, 50:4, 407-420, DOI: 10.1080/07055900.2012.707610

Yao, Y., Perrie, W., Zhang, W., Jiang, J. 2008. The characteristics of atmosphere-ocean interactions along North Atlantic extratropical storms tracks. *Journal Geophys. Res.*, 113, D14124, doi:10.1029/2007JD008854

Yin, J. 2012. Century to Multi-Century Sea Level Rise Projections from CMIP5 Models. Geophysical Research Letters. Vol. 39. 7 pp.

APPENDIX: References produced by companion oceanographic trends and projections ACCASP team

Brickman, D., B. DeTracey, Z. Long, L. Guo, and W. Perrie. 2013. Analyses of CRCM output for emergence times of climate changes in air temperature and wind speed. Ch. 12 (p. 171-182) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Caissie, D. 2013. Impact of climate change on water temperatures for selected rivers in New Brunswick and potential implications on Atlantic salmon. Ch. 13 (p.183-190) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Chassé, J., N. Lambert and D. Lavoie. 2013a. Precipitation, evaporation and freshwater flux over Canada from six Global Climate Models. Can. Tech. Rep. Hydrogr. Ocean Sci. 287: viii + 47 p. http://www.dfo-mpo.gc.ca/Library/349263.pdf

Chassé, J., W. Perrie, Z. Long, D. Brickman, L. Guo and N. Lambert. 2103b. Regional atmosphere-ocean-ice climate downscaling results for the Gulf of St. Lawrence using the DFO Regional Climate Downscaling System. Can. Tech. Rep. Hydrogr. Ocean Sci. (under revision)

DFO (2013). Risk-based assessment of climate change impacts and risks on the biological resources and infrastructure within Fisheries and Oceans Canada's mandate – Atlantic Large Aquatic Basin. Fisheries and Oceans Canada, Can. Sci. Sec. Sci. Resp. 2012/044. 40 p. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2012/2012_044-eng.html

Galbraith, P. S. and P.. Larouche. 2013. Trends and variability in eastern Canada sea-surface ocean temperatures. Ch. 1 (p. 1-18) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Galbraith, P. S., D. Hebert, E. Colbourne, and R. Pettipas. 2013. Trends and variability in eastern Canada sub-surface ocean temperatures and implications for sea-ice. Ch. 5 (p. 57-72) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Hamilton, J. and Y. Wu. 2013. Synopsis and trends in the physical environment of Baffin Bay and Davis Strait. Can. Tech. Rep. Hydrogr. Ocean Sci. 282: vi + 39 p. http://www.dfo-mpo.gc.ca/Library/348087.pdf

Han, G., N. Chen and Z. Ma. 2013a. Interannual-to-decadal variations of the Labrador Current. Ch.7 (p. 85-94) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren

(Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Han, G., Z. Ma, and H. Bao. 2013b. Trends of temperature, salinity, stratification and mixed-layer depth in the Northwest Atlantic. Ch. 2 (p. 19-32) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Han, G. E. Colbourne, P. Pepin, and R. Tang. 2013c. Statistical projections of physical oceanographic variables over the Newfoundland and Labrador Shelf. Ch. 6 (p. 73-84) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Han, G., Z. Ma, J. Loder, H. Bao and A. van der Baaren. 2013d. Mean sea level trends in the Northwest Atlantic: Historical estimates and future projections. Ch. 9 (p. 113-126) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Hebert, D. 2013a. Trends in temperature, salinity, density and stratification for different regions in the Atlantic Canadian shelf. Ch. 3 (p. 33-42) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Hebert, D. 2013b. Trends in temperature, salinity, density and stratification in the upper ocean for the Scotian Shelf. Ch. 4 (p. 43-56) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Lambert, N., J. Chassé, W. Perrie, Z. Long, L. Guo and J. Morrison. 2013. Projection of future river runoffs in Eastern Atlantic Canada from Global and Regional climate models. Can. Tech. Rep. Hydrogr. Ocean Sci. 288: viii+34 p. http://www.dfo-mpo.gc.ca/Library/349262.pdf

Lavoie, D., N. Lambert. S. ben Mustapha and A. van der Baaren. 2013a. Projections of future physical and biogeochemical conditions in the Northwest Atlantic from CMIP5 Global Climate Models. Can. Tech. Rep. Hydrog. Ocean Sci. 285: xiv + 156 p. http://www.dfo-mpo.gc.ca/Library/349066.pdf

Lavoie, D., N. Lambert and A. van der Baaren. 2013b. Projections of future physical and biogeochemical conditions in Hudson and Baffin Bays from CMIP5 Global Climate Models. Can. Tech. Rep. Hydrog. Ocean Sci. 289: xiii + 129 p.http://www.dfo-mpo.gc.ca/library/349552.pdf

Loder, J.W. and A. van der Baaren. 2013. Climate change projections for the Northwest Atlantic from six CMIP5 Earth System Models. Can. Tech. Rep. Hydrogr. Ocean Sci. 286: xiv + 112 p. http://www.dfo-mpo.gc.ca/library/349550.pdf

Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.). 2013. Aspects of climate change in the Northwest Atlantic off Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x +190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Loder, J.W., Z. Wang, A. van der Baaren and R. Pettipas. 2013c. Trends and variability of sea surface temperature (SST) in the North Atlantic from the HadISST, ERSST and COBE datasets. Can. Tech. Rep. Hydrogr. Ocean Sci. 292: viii + 36 p. http://www.dfo-mpo.gc.ca/Library/350066.pdf

Pepin, P., G.L. Maillet, D. Lavoie and C. Johnson. 2013. Temporal trends in nutrient concentrations in the northwest Atlantic basin. Ch. 10 (p. 127-150) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p. http://www.dfo-mpo.gc.ca/Library/350208.pdf

Peterson, I.K. and R. Pettipas. 2013. Trends in air temperature and sea ice in the Atlantic Large Aquatic Basin and adjoining areas. Can. Tech. Rep. Hydrogr. Ocean Sci. 290: v + 59 p. http://www.dfo-mpo.gc.ca/Library/350061.pdf

Thistle, M.E. and Caissie, D. 2013. Trends in air temperature, total precipitation and streamflow characteristics in eastern Canada. Can. Tech. Rep. Fish. Aquat. Sci. 3018: xi + 97 p. http://www.dfo-mpo.gc.ca/Library/347639.pdf

Xu, Z., D. Lefaivre and M. Beaulieu. 2013. Sea levels and storm surges in the Gulf of St. Lawrence and its vicinity. Ch. 8 (p. 95-112) *In:* Aspects of climate change in the Northwest Atlantic off Canada [Loder, J.W., G. Han, P.S. Galbraith, J. Chassé and A. van der Baaren (Eds.)]. Can. Tech. Rep. Fish. Aquat. Sci. 3045: x + 190 p.